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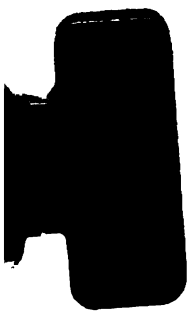

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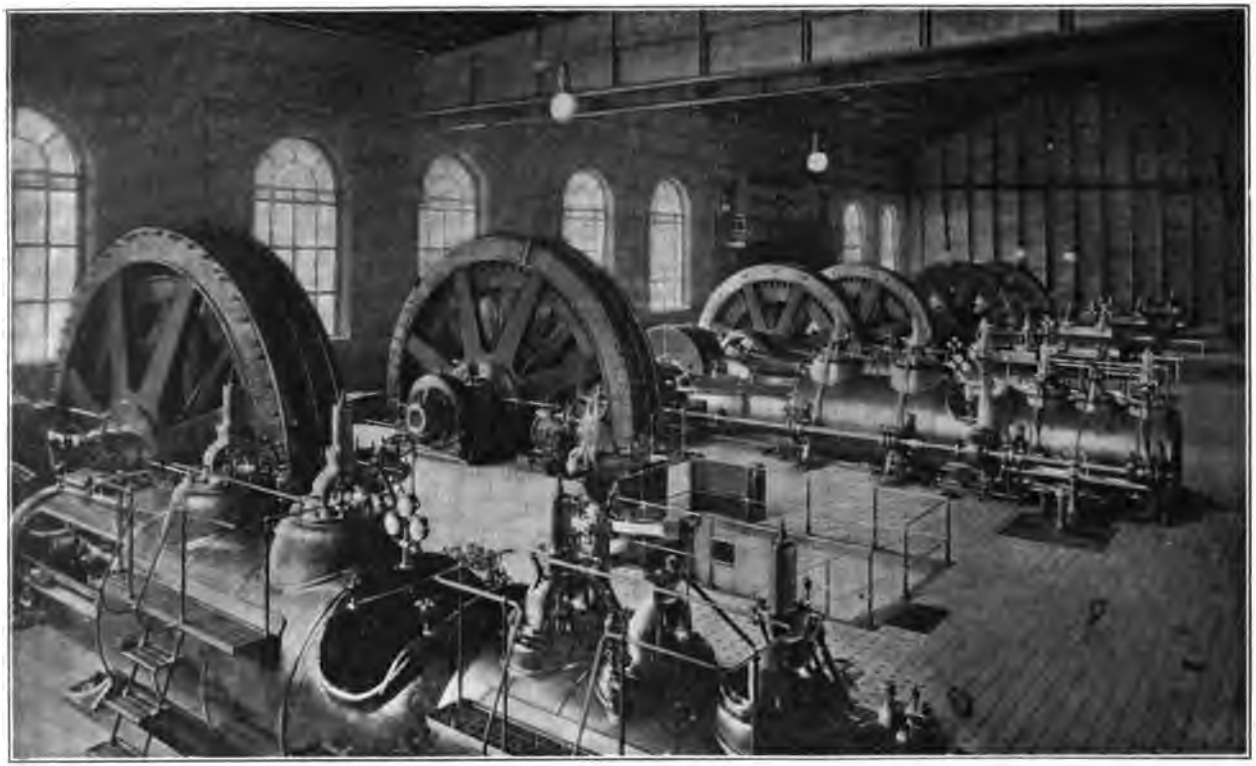

LARGE CENTRAL STATION SHOWING REPRESENTATIVE PRACTICE IN DRIVING GENERATORS.

MODERN ENGINEERING PRACTICAL STUDY

ELECTRICITY · MECHANICS

VOLUMES

EDITOR-IN-CHIEF

FRANK W. GUNSAULUS

PRESIDENT ARMOUR INSTITUTE OF TECHNOLOGY

Assisted by a large corps of Distinguished Specialists and Technical Experts

VOLUME VI

ELECTRICITY—GENERATORS—MOTORS

AMERICAN SCHOOL of CORRESPONDENCE
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AMERICAN SCHOOL of CORRESPONDENCE at ARMOUR INSTITUTE of TECHNOLOGY

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Volume VII.

ELECTRICITY: GENERATORS MOTORS
TELEGRAPH AND TELEPHONE

SECTION I.

ELEMENTS OF ELECTRICITY.

Electricity is an invisible agent which manifests itself in various ways. The precise nature of electricity is not known, but the effects produced by it, the methods of controlling it, and the laws governing its action are becoming well known.

Electricity may be considered under three heads: first, **magnetism,** — second, **static** electricity (where it appears as a *charge* upon bodies),— and third, — **dynamic** electricity (where it appears as a *current*). The sciences which treat of the two latter branches are called *electrostatics* and *electrodynamics* respectively. These divisions of the subject, although covering manifestations widely different, are closely related.

MAGNETISM.

Natural Magnets. Substances which have the property of attracting pieces of iron are called *magnets.* A material possessing this property was first found by the Ancients at Magnesia, in Asia Minor, from which fact arose the name *magnet.* The natural magnet is an oxide of iron and is also called the *lodestone.* It is widely distributed in different parts of the world, but is not always found possessing magnetic properties.

Artificial Magnets. When a bar of hard steel is rubbed with a lodestone, the steel will acquire the same magnetic property and to a much greater extent. Such artificial magnets are therefore always used in place of lodestones.

Poles. When one end of a magnet is placed in iron filings and afterwards withdrawn, the filings are attracted and cling to it in great numbers. This is illustrated in Fig. 1. The filings would be attracted to the opposite end and would cling to it in the same way if it were placed in the filings. The middle of the bar, however, does not have this property, and toward the ends the power rapidly increases. The ends of the magnet, where the attraction is the greatest, are called *poles.*

A common example of a magnet is the compass needle. It is well known that such a needle always places itself so as to point

north and south, and that the same pole always points toward the north. This is called the *north seeking pole*, while the other is called the *south seeking pole*, or simply the north and south pole respectively.

In the experiment with iron filings either of the magnetic poles

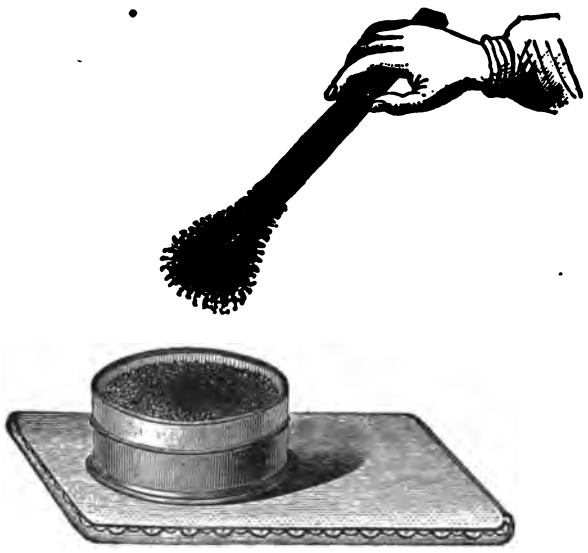


Fig. 1.

attracts them and there is apparently no difference between the two poles. That there is a difference, however, may be shown by experimenting with two compass needles. If the north poles of two such needles be brought near each other, they will be *repelled*. In the same way the south poles will repel each other. But when

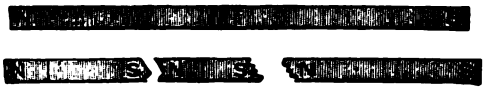


Fig. 2.

the north pole of one needle is brought near the south pole of the other, *attraction* takes place. This shows that *like poles repel* each other, while *unlike poles attract* each other.

The fact that a compass needle always points north and south, or approximately so, is because the earth itself is a great magnet. The magnetic poles of the earth coincide very nearly

with the geographical north and south poles. The geographical north pole of the earth is unlike the north pole of a magnetic needle, and hence attracts it.

The two poles always exist in a magnet. If, as illustrated in Fig. 2, a single magnet be broken into several parts, the separate parts will then become individual magnets. Each portion will have the same properties which the magnet as a whole possessed. When the separate parts are placed together again the many poles of the small portions will neutralize each other and the complete magnet will act as before.

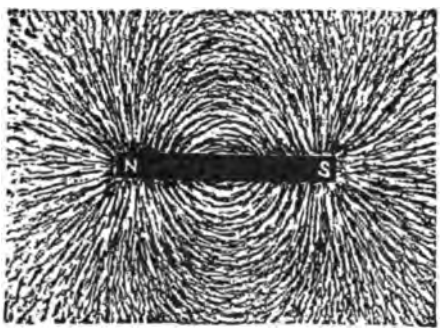


Fig. 3.

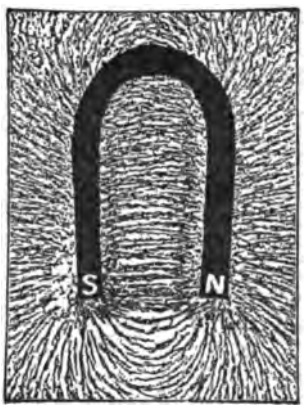


Fig. 4.

Magnetic Field. The space surrounding a magnet, called the field, is subject to the influence of the magnet and is called its *magnetic field.* The presence of such a field may be shown by a simple experiment.

Suppose a sheet of paper be placed upon a bar magnet and iron filings spread evenly upon the paper; by tapping the paper lightly, the filings will form into a series of curved lines extending from one pole to the other. The form of these curves for a bar magnet is illustrated in Fig. 3. The formation of these definite curves indicates that the magnetic field exerts its influence in certain definite directions which are called the *lines of magnetic force*, or simply *lines of force.* The field of a horseshoe magnet is represented in Fig. 4, and that about the end of a bar magnet is represented in Fig. 5.

Magnetic Induction. It is because of this magnetic field that magnets have the power of attracting pieces of iron. When a piece of iron is brought under its influence, it becomes a *temporary* magnet, and for the time being has its two poles. If the north pole of the permanent magnet is adjacent to the piece of iron, a south pole will be induced in the iron next to this north pole and a north pole in the portion farthest from it. The attraction is then exactly similar to the attraction between two permanent magnets when unlike poles are brought together. This action of developing magnetism in iron is called *magnetic induction.*

The attraction of iron is therefore due to the fact that the

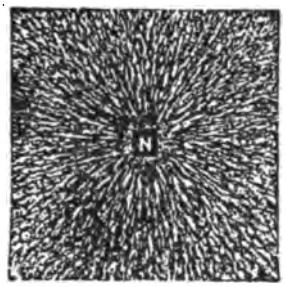


Fig. 5.

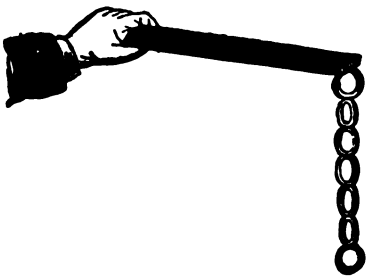


Fig. 6.

magnet first magnetizes it and then attracts it. When the iron is withdrawn from the magnetic influence it loses its magnetism. The experiment illustrated in Fig. 6 proves this to be true. When the upper ring of soft iron is placed in contact with the bar magnet it becomes a magnet, having, say, a north pole at the top and a south pole at the bottom. When another ring is added, the first will in turn induce a north pole at the top and a south pole at the bottom of the second ring. When other rings are added, a similar action takes place and all the rings are supported. If, however, the first ring be removed, the others will immediately drop and will lose their magnetism.

Magnetic induction explains the formation of tufts of iron filings which become attached to the poles of magnets. The filings are temporarily converted into magnets; these act inductively

on the adjacent parts, these again on following ones, and so on, causing them all to be attracted. They have a bush-like appearance, which is due to the repulsive action that the outside free poles exert upon each other.

The attraction is greatest when the iron is in contact with the magnet, but actual contact is unnecessary to cause attraction. A sheet of glass, paper or wood, etc., may be placed between the magnet and the iron, and attraction will still be present.

Magnetic Substances. Substances which are attracted by magnets when either pole is presented to them are called *magnetic substances*. Besides iron are included steel, nickel and cobalt in this class. A magnet is attracted or repelled by another magnet according to whether the poles near each other are unlike or like, but magnetic substances are always attracted.

Retentivity. After a piece of soft iron is once magnetized it will, when removed from the influence of the magnet, lose substantially all of its magnetism. On the other hand, a piece of steel or nickel will not be magnetized as much as soft iron, but will afterwards retain much of its magnetism. It resists being magnetized, and afterwards resists being demagnetized. This power of resisting magnetization or demagnetization is called *retentivity*. Steel has much greater retentivity than wrought iron, and the harder the steel the greater is the retentivity.

Methods of Magnetization. Permanent magnets are usually made from steel, and the following are the common methods of magnetization:

Magnetization by *single touch* consists in moving the pole of a powerful magnet from one end to the other of the bar to be magnetized, and repeating this operation several times, always in the same direction. The end of the bar touched last by the magnet becomes of opposite polarity to the end of the magnet by which it has been touched. This method produces only a weak magnet, and is therefore used for small magnets only.

Magnetization by *divided touch* consists in placing the two unlike poles of two magnets at the middle of the bar to be magnetized, and in moving them simultaneously towards the opposite ends of the bar. Each magnet is then placed in its original posi-

tion and the operation repeated. The bar becomes magnetized after repeating this several times on both faces of the bar.

In magnetization by *double touch* the two magnets are placed as before, with opposite poles near each other, at the middle of the bar to be magnetized. Instead of moving them in opposite directions toward the ends, they are kept at a fixed distance apart by means of a piece of wood between them, and are simultaneously moved first towards one end and then back towards the other, repeating several times and stopping at the middle.

Magnets lose much of their magnetism when subjected to knocks or jars.

STATIC ELECTRICITY.

Friction as a Source. There are several sources of electricity, such as friction, chemical action, heat and induction. Friction as a source of electricity will now be considered. This relates to electricity existing as *charges* upon bodies, and is known as *static electricity*.

When a glass rod or stick of sealing-wax is rubbed with a piece of flannel or silk, each acquires the property of attracting light bodies such as pieces of wool, paper, gold leaf, etc. After coming into contact with such substances, however, they will be repelled. This may be well observed by employing a pith ball suspended by a fine thread, as shown in Fig. 7. When the rod of glass or wax is brought near the ball it is strongly attracted. After contact is made, the ball will be strongly repelled.

This repulsion is explained by the fact that when contact is made between the ball and rod, the ball receives part of the electricity from the rod. Both are then charged with the same kind of electricity, and the repellant action shows that two bodies thus charged, repel each other.

Positive and Negative Electricity. Repulsion does not always take place between bodies charged with electricity. Either a stick of sealing-wax or a glass rod after being rubbed with silk will attract the pith ball until contact has been made, and then will repel it. The electricity developed in each of these cases, however, is not the same. After the pith ball has been touched with an electrified glass rod, it will be *attracted* by the electrified stick of sealing-wax; or if touched by the latter, it

will be repelled by it, but will be *attracted* by the glass rod. Such phenomena are explained by assuming that there are two kinds of electricity, which have been designated as *positive* (+) and *negative* (—) electricity.

When the glass rod is rubbed with silk it is said to possess a positive charge, and when the wax is rubbed it is said to possess a negative charge. The pith ball having been touched by the glass rod is charged positively, and is therefore attracted by the negatively charged sealing-wax, or upon receiving a negative charge from the wax, it will be attracted by the glass.

This action is expressed in the following law:

Electric charges of the *same* sign *repel* each other; those of *opposite* sign *attract* each other.

Production of Both Positive and Negative Electricity. When two substances are rubbed together neither positive nor negative electricity is produced alone, but both are produced at the same time and in equal quantities. After the friction, a positive charge is found to exist upon one surface and a negative charge upon the other and in equal quantities. In the case of glass being rubbed by silk, the glass acquires a positive charge and the silk a negative charge. That the charges are equal is proved by the fact that if both of these charged bodies are presented to the pith ball at once, the latter will be neither attracted nor repelled. Also if the charges of both the glass and silk are imparted to a third body, the third body will have no resultant charge, since the two quantities of electricity being equal and of opposite sign, neutralize each other.

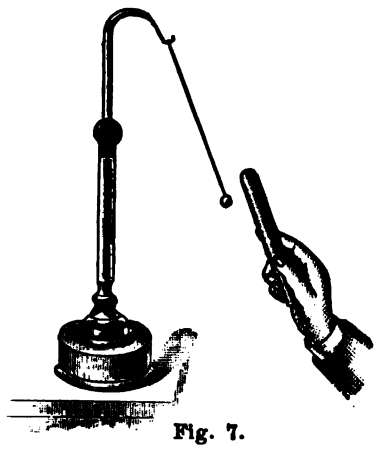


Fig. 7.

Whether a body receives a positive or negative charge depends upon the material of the body with which it makes contact. Thus glass when rubbed by silk is positively charged, but when rubbed by wool the glass is negatively charged. In the

following list the arrangement is such that each substance, when rubbed by one following it, will be positively electrified, but when rubbed by one preceding it, will be negatively electrified: Fur, wool, ivory, glass, silk, wood, metals, sealing-wax, sulphur, india-rubber, celluloid.

Conductors and Insulators. *Conductors* are substances which readily allow electricity to pass from one portion of them to another; that is, they readily conduct electricity. *Insulators*, or non-conductors, are those substances which do not allow such free passage of electricity, or which offer a certain *resistance* to its passage. If one end of a glass rod is rubbed with silk or wool, the end so rubbed will be electrified, but the other end will possess little or no charge. The electricity is not freely conducted from one part to another. When a metallic substance is charged, however, the electricity will be distributed uniformly over its surface. All substances offer a certain amount of resistance to the passage of electricity and no body entirely prevents its passage; that is, there is no perfect conductor, and there is no perfect insulator.

There is no definite line of distinction between conductors and insulators, and some substances are neither, but may be termed semi-conductors or partial conductors. The ability of a body to conduct electricity, that is, its *conductivity*, also depends upon its physical condition. For example, the conductivity of most bodies depends largely upon the temperature. The following list of substances is arranged in the order of increasing resistance.

Conductors.	*Partial Conductors.*	*Insulators.*
Silver	Cotton	Oils
Copper	Dry wood	Porcelain
Other metals	Marble	Wool
Charcoal	Paper	Silk
Water		Resin
The body		Guttapercha
		Shellac
		Ebonite
		Paraffin
		Glass
		Air

From the preceding it is evident that silver is the best conductor and air is the best insulator. Copper, on account of being an excellent conductor and comparatively cheap, is used almost entirely for conducting electricity from power stations or from one point to another. Marble is a comparatively poor conductor and is therefore largely used for switchboards. Porcelain and glass, being good insulators and having other desirable properties, are much used for insulating conductors from their main supports. Water is a fairly good conductor, and considerable difficulty is consequently experienced in securing good insulation in damp places.

Distribution of Charge. An electrical charge upon a conducting body is distributed over its *surface*. That it does not reside *within* the body may be shown in several different ways. For example, it is immaterial whether the inside of a conductor is composed of wood or glass, or if the conductor is hollow; the charge in any case is distributed over its surface.

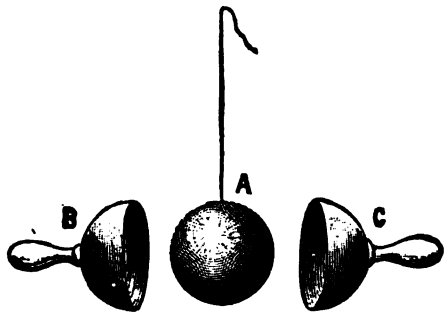


Fig. 8.

The ball *A* and covers *B* and *C*, shown in Fig. 8, may be used to prove this. Suppose the covers to be placed over the ball and the whole to be electrified. When the covers are removed, the entire charge will be found to remain with them, and none will exist upon the ball.

Suppose the hollow sphere in Fig. 9 to be charged. If a conductor be inserted through the aperture and brought in contact with the inside of the sphere and afterwards carefully withdrawn, it will be found that it has received no charge. If touched to the outside, however, the conductor will receive part of the charge. The conductor used for this purpose may be a thin piece of metal attached to an insulating handle. A metallic cylinder, even of wire gauze, may be used in place of the sphere. To prevent the charge from passing to the earth, the cylinder or sphere must be insulated from the earth by a glass standard.

We have seen that bodies charged with electricity of like sign repel each other. This may be taken as the explanation of the fact that a charge resides upon the surface. As it tends to repel itself, the charge resides as far from the centre of the body as possible.

Static Influence. When a charged body is placed near bodies in a neutral state, it will act upon them in a manner similar to that of a magnet upon soft iron. This action is said to be due to influence or to *electrostatic induction.*

Induction of this nature may be made evident by means of a metal cylinder supported on a glass standard, as shown in Fig. 10. The cylinder is supplied at each end with a pith ball suspended by a thread. Suppose a sphere charged with positive electricity and mounted upon an insulating standard be brought near one end of the cylinder; the pith balls will at once fly outwardly, showing that the cylinder is then charged. If the sphere is removed, the pith balls will fall towards the ends of the cylinder again, showing that it is once more in the neutral state. Throughout this action the sphere has neither gained nor lost in the amount of its charge. Upon testing the temporary charge on the cylinder, it will be found that at the end near the sphere the electricity is negative while that at the distant end is positive.

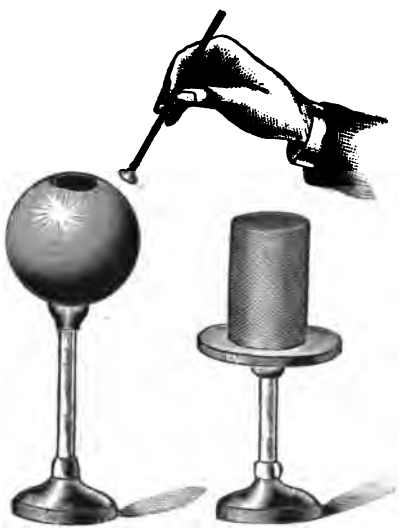


Fig. 9.

Bodies charged with electricity are surrounded by an electric field in the same way that magnets are surrounded by a magnetic field. With this in mind, the above experiment may be easily understood. When the charged sphere is brought near the cylinder, the latter comes under the influence of the former's field. The lines of force from the sphere will pass to the cylinder, and therefore cause its electrification. Since unlike charges attract

each other and like charges repel each other, the sphere attracts a negative charge to the near end and repels a positive charge to the distant end of the cylinder. When the sphere is removed, the induced positive and negative charges neutralize each other. If the sphere possessed a negative charge, there would then be induced a positive charge at the near end and a negative charge at the distant end of the cylinder. The middle portion of the cylinder, however, remains neutral, and the strength of the charges increases gradually towards the ends. If the cylinder be separated into two parts while under the influence of the charged body, the induced charges cannot unite after the removal of the sphere, and will then retain their charges.

In the experiment illustrated by Fig. 10, there is consider-

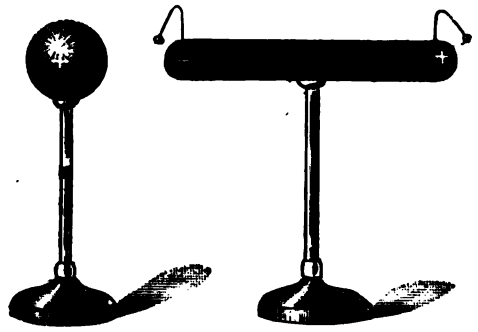


Fig. 10.

able attraction exerted between the sphere and cylinder. The unlike and adjacent charges attract each other, but the like charges on the sphere and distant end of the cylinder repel each other. As the unlike charges are nearer each other than the like charges, the attraction overbalances the repulsion and there is a resultant attraction. This action is the same in effect as that of magnets upon soft iron. There is first the induction and then the consequent attraction.

The greater the charge possessed by the sphere, the greater will be the induced charge upon the cylinder. Also, the nearer the two bodies are placed to each other, the greater becomes the charge upon the cylinder, but the induced charge can never exceed that on the sphere.

When the distance between the sphere and cylinder is grad-

ually decreased, the attraction between the unlike charges is increased. This will continue until the attraction is so great that the unlike charges abruptly unite, and in so doing cause a spark to appear in the small intervening space. The unlike charges are thus neutralized, but the repelled charge will still remain upon the cylinder.

Free and Bound Charge. The two charges induced in the cylinder may be called free and bound charges. The unlike induced charge, which is represented as negative in Fig. 10, is referred to as the bound charge, because it is attracted by the charge upon the sphere and is thus confined. The repelled charge, however, may escape by any path which is offered, and is therefore called the free charge. Hence if contact be made between the cylinder and the earth, the repelled charge will pass to the ground and the attracted charge will remain. If the contact with the earth is then broken and the sphere removed, a resultant charge will remain upon the cylinder, which will be opposite in kind to that of the sphere. This resultant induced charge will then distribute itself uniformly over the cylinder and may be used to induce other charges.

Fig. 11.

When bodies are thus charged by induction, the charge is always opposite in kind to that inducing it. On the other hand, when bodies are charged by conduction or by making direct contact, the charge imparted is of the same kind. Poor conductors are not readily acted upon by induction, since they present great resistance to the passage of electricity.

Electroscope. An electroscope is an instrument used for detecting the presence and determining the kind of electricity in any body. The gold-leaf electroscope shown in Fig. 11 is one of the common forms, and is a very sensitive instrument. It

consists of a glass jar with a metal rod passing through the stopper and terminating at the lower end in two strips of gold leaf, and at the upper end in a metal plate or knob.

When a charged body is brought near the plate, an unlike charge is induced therein, while a like charge is repelled to the two strips of gold leaf. The two strips, being then similarly charged, repel each other and diverge. When the charged body is withdrawn, the strips will come together again. A rubbed glass rod will cause the strips to diverge even when two or three feet from the plate.

In order to determine the kind of electrification a body possesses, the plate is first touched by a body charged with a known kind of electricity, say positive. The electroscope is then charged with positive electricity and the strips of gold diverge. The body to be tested is then brought near the plate. If the gold leaves then diverge more, the body is charged with positive electricity, but if they approach each other, the body is charged with negative electricity.

Fig. 12.

Electrophorus. This is an apparatus by which an unlimited number of charges may be obtained from a single charge. It consists of a round cake of resinous material (Fig. 12), formed in a shallow metal pan, and a round metal plate of slightly smaller diameter, provided with a glass handle. In using the electrophorus, the resin is first rubbed with a woolen cloth or with a cat's skin, and receives a charge of negative electricity. The plate is then placed on the cake. Owing, however, to the unevenness of the resin, the plate comes in contact with only a few points, and on account of the non-conductivity of the resin, the negative electricity of the cake does not pass to the plate. On the contrary, it acts by induction on the plate and attracts a positive charge to the under surface and repels a negative charge to the upper. The plate is now touched with the finger, and the induced negative electricity being repelled and free, passes off. The plate then retains a bound charge of positive electric-

ity and, when raised from the cake, the charge distributes itself uniformly over the surface. The charge is sufficient to yield a spark when another conductor is brought near the plate. The plate may then be replaced, touched, and when removed will possess another charge. The original charge on the cake, however, remains substantially the same in amount.

It may appear from the above that there is a gain in energy without a corresponding expenditure of work. This is not the case, however, for every time the plate is raised, the attraction between the unlike charges must be overcome and work is therefore expended in raising the plate.

Electric Machines. The electrophorus is a very elementary form of electric machine, but there are other types which are much more powerful. One type operates upon the same princi-

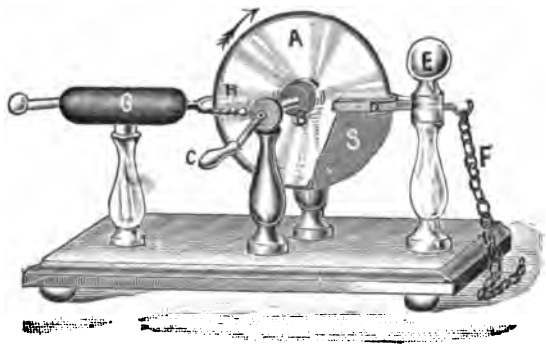


Fig. 13.

ples as the electrophorus; the initial charge induces other charges, which are conveyed by the moving parts of the machine to some other part, where the induced charges may be accumulated. In another type the electricity is produced by friction. Fig. 13 illustrates the plate electric machine which is of the frictional type. The machine consists of a plate, *A*, of glass or ebonite, having its shaft, *B*, provided with a handle, *C*. A pair of rubbers or cushions, *D*, press against opposite sides of the glass and are in electrical connection with the insulated negative conductor *E*. The cushions are usually made of leather and covered with an amalgam of tin, zinc and mercury. The prime conductor *G* is supported by an insulating standard and carries two arms,

H, which extend one on each side of the plate. These arms carry teeth in the form of combs which extend inwardly, but are not in contact with the plate. Electricity tends to escape from sharp or pointed projections, and round, polished surfaces are best adapted to retain a charge. A silk flap *S* is attached to the cushions and partially covers the plate.

When the handle is turned, the frictional contact causes the rubber to be negatively electrified and the plate positively. The positive charge is carried around on the plate and acts inductively upon the prime conductor *G*, repelling a positive charge to its distant end and attracting a negative charge. The negative electricity, being attracted by the positive charge on the plate, passes readily to it by means of the combs *H*, and these charges are thereby neutralized. Hence that portion of the plate which has passed the combs retains no charge, but an induced, positive charge accumulates on the conductor *G*. Upon passing the cushions, that portion of the plate is recharged, and the action is repeated. The lower half of the plate is therefore always charged, and the other half is neutral. As each successive part of the plate passes the cushion it receives a positive charge, which is neutralized when it passes the combs. The flap *S* is used to reduce electrical leakage from the plate. When positive electricity is to be collected on *G*, conductor *E* is put in connection with the earth by means of a chain or wire, *F*. The negative electricity of the cushions is thereby neutralized. Negative electricity may be collected upon conductor *E*, by connecting *G* to ground instead of conductor *E*.

Condensers. A condenser is an apparatus for accumulating a large quantity of electricity on a comparatively small surface. The form may vary considerably, but in all cases it consists essentially of two conductors separated by a non-conductor, and its action depends upon induction.

In explaining the action of the condenser, the apparatus illustrated in Fig. 14 will be considered. The two plates *A* and *B* are insulated conductors, and *C* is a glass plate between them. Each of the conductors has a pith ball *a* and *b* connected with it. Let plate *A* at first be at such a distance from *B* as to be out of its sphere of influence. The plate *B* is then connected by the

conductor x, to the positive conductor of an electrical machine, and receives a positive charge, which is distributed uniformly over its surface. The pith ball or pendulum b will diverge widely, and if connection with the charging machine then be broken, no change in the distribution of the electricity occurs. However, when plate A is placed in the position shown, the distribution is considerably changed. This plate is connected to the earth by a conductor y. The positive charge on B now acts inductively across the intervening space and glass-plate C, repelling a positive charge to the earth through y, and attracting a negative charge which resides on the face n of plate A. This negative charge now reacts upon the positive of plate B and attracts it. The uniform distribution on this plate is then disturbed and the positive electricity accumulates on the face m of plate B. That the density of charge on the other portions of conductor B is diminished, is shown by the fact that pendulum b diverges less. Owing to there being less electricity on portions of B than before, B can be recharged until the pendulum diverges as much as at first. The

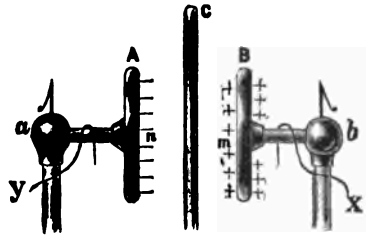


Fig. 14.

effect of plate A, therefore, is to condense the electricity on face m of plate B and thus increase its capacity for more electricity. Electricity is then distributed over the entire surface of B, but is much more dense on face m. If the connections x and y be broken and the plates separated so that they have no effect upon each other, the positive charge will then be distributed equally over the surface of B, and the negative charge equally over surface A. This is shown by the pendulums diverging much more than before.

The nearer the plates A and B are to each other, and the greater their size, the greater the capacity of the apparatus; that is, the greater may be the charge on B.

Leyden Jar. The Leyden jar is the most convenient form of condenser. It consists, as shown in Fig. 15, of a glass jar, coated within and without for about two-thirds of its height with tin foil. The stopper has a metallic rod passing through it which communicates with the inner coating by means of a small chain. The upper end of the rod terminates in a knob. The upper portion of the jar, the stopper and the supporting rod are usually coated with shellac to protect them from moisture. The inner coating corresponds to the collecting plate *B* of Fig. 14, the glass to the insulating plate *C* and the outer coating to the condensing plate *A*.

The jar is charged by holding the knob to the prime conductor of an electrical machine or other source of electricity, and connecting the outer coating to the earth by a wire or chain, or by holding the jar in the hand. When the knob is presented to the positive conductor of the machine, positive electricity is accumulated on the inner coating and negative electricity on the outer coating. The positive charge acts inductively through the glass and repels a positive charge to the earth and attracts a negative charge on the inner face of the outer coating. The action of the jar is therefore the same as that of the condenser previously considered.

Fig. 15.

The jar should be made of good glass, should be kept dry and free from dust. The thinner the glass the greater is the capacity, but if the glass is too thin it will not be effective in insulating the charges from each other. In such a case a spark will pass from one coating to the other directly through the glass.

The jar may be discharged by connecting the inner and outer coatings by a conductor. If the outer coating be held in one hand, and the other hand be presented to the knob the person will experience a severe shock, as the arms and body then provide a path for the electricity to unite. To eliminate danger in discharging, a pair of discharging tongs should be used. These consist of jointed brass rods provided with knobs at the separable ends and also provided with insulating handles. One of the knobs is brought in contact with the outer coating and the other

brought near the knob connected to the inner coating. A bright spark then leaps between these two knobs and the discharge is accomplished.

For the accumulation of powerful charges, a *battery* of jars is used. This consists of several jars, which have all the inner coatings or knobs connected together and all the outer coatings connected together. The battery is charged and discharged in the same manner as a single jar; in fact, the battery is equivalent to a single jar having very large inner and outer coatings. Great care must be taken in charging or discharging a battery, as a shock received may be serious enough to prove fatal.

DYNAMIC ELECTRICITY.

Dynamic electricity, or electrodynamics, considers the flow of electricity in *currents*. In the preceding pages the static charge has been considered, but it has been shown that such a charge may pass readily from one conducting body to another when a suitable path is provided. If electricity could be supplied just as fast as it flowed away, there would be a continuous flow, or current of electricity. Hence if one end of a wire is kept positive and the other negative, electricity constantly flows from one end to the other. This result may be obtained by chemical action, heat or induction. The latter method, which includes the movement of wires across a magnetic field is used in the dynamo and is fully considered in the following discussions. In all cases when a continuous current flows there must be a complete curcuit provided.

Voltaic Cell. A continuous current is obtained from the voltaic cell, and the source of the electricty is the chemical action. Such a cell is illustrated in Fig. 16. The glass jar A contains dilute sulphuric acid, in which are placed the copper plate C and the zinc plate Z. When a wire connects the two plates as shown, a continuous flow of electricity takes place (as indicated by the arrows) from the copper plate through the wire to the zinc plate and through the liquid to the copper plate. The flow of current tends to neutralize the difference in electrical condition of the plates, but the chemical action within the jar maintains this difference. This electrical difference between the plates is called the *potential* difference; and the greater the amount of

potential difference, the greater is said to be the *pressure, electromotive force* or *voltage*, which causes a current to flow. The strength of the current passing depends directly upon the amount of this electromotive force. The current strength also depends upon the amount of *resistance* to its flow. If the circuit is short and made up of good conductors, the current will be much stronger than if it were long and made up of poor conductors.

Flow of Electricity. Electricity, although commonly described and referred to as *flowing* through a circuit does not actually *flow*. There is no transfer of matter along the circuit. A wire carrying a current looks the same as one that is not, and that electricity is present is only evident by the heating, chemical or magnetic effects produced. It is convenient, however, to describe electricity as flowing, and this term suffices for all practical purposes.

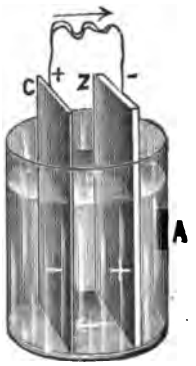


Fig. 16.

In order to show the relation between electromotive force, current and resistance, electricity flowing in a circuit is often compared to the flow of water in a pipe which connects two reservoirs containing water at different levels. When a clear path is provided, the water will flow from the reservoir at the higher level to the one at the lower level, and the greater the difference in the levels the greater is the pressure and consequent flow of water. Also the water will flow much faster through a short large pipe, than through a long and small one. Similarly, the greater the pressure or electromotive force the stronger is the current of electricity, and the greater the resistance of the circuit the less the current. This analogy must not be too closely applied, however, for the reason that with water there is an actual transfer of matter.

Internal and External Resistance. The circuit shown in Fig. 16 may be divided into two parts,—the *internal*, which includes the plates and liquid, and the *external* circuit which consists of the wire connecting the plates. If this wire is small and long, it will have a high resistance and only a weak current will flow. The resistance of liquids as compared with metals is con-

siderable. The internal resistance of a cell may be reduced by having the plates large and putting them close together. Gases are poor conductors of electricity, and hence the bubbles caused by the chemical action and which cling to the plates, greatly increase the internal resistance.

Fig. 17.

Fig. 18.

Chemical Action in the Cell. The essential elements of a voltaic cell are: a plate, which may be oxidized, such as zinc, a liquid capable of acting on this plate, such as sulphuric acid, and an inactive plate, such as copper. When the wire connecting the plates is broken, there is no current, but upon closing the circuit chemical action takes place and a current flows. The chemical reaction which occurs is represented as follows:

$$Zn + H_2SO_4 = ZnSO_4 + H_2,$$

which is equivalent to saying that the zinc (Zn) combining with the sulphuric acid (H_2SO_4), produces zinc sulphate ($ZnSO_4$) and free hydrogen gas (H_2). The hydrogen is given off as a gas from the liquid and zinc sulphate remains in solution. This action takes place as long as the current flows and depends upon the amount of current flowing. The zinc gradually dissolves into the liquid and the latter gradually becomes a solution of zinc sulphate. When the liquid no longer contains any acid or when the zinc is used up, the chemical action ceases. The spent liquid must then be replaced by a new acid solution and a new piece of zinc substituted.

Polarization. One great objection to the simple voltaic cell is that the current produced, rapidly decreases in strength after the circuit is closed for a short time. This is due mainly to the collection of hydrogen bubbles upon the surface of the copper plate. This coating of bubbles hinders the direct contact of the copper plate with the liquid as its effective area is reduced. This also greatly increases the internal resistance of the battery.

When this accumulation of hydrogen bubbles takes place, the cell is said to be polarized. In order to reduce this action and so enable a cell to maintain a constant current for some time, single fluid cells have been largely replaced by double fluid cells. In these the inactive plate, about which the bubbles would otherwise collect, is placed in a liquid which chemically unites with the hydrogen.

Among the numerous forms of cells now manufactured, the following are described as being among the most important.

Smee's Cell. In this cell, which is illustrated in Fig. 17, polarization is reduced by mechanical means. The cell consists of a silver plate, coated with a deposit of finely divided platinum, and suspended between two zinc plates in dilute sulphuric acid. The middle plate has a roughened surface due to the deposit of platinum, and the hydrogen bubbles therefore readily disengage from its surface and pass off.

Bichromate Cell. This cell, shown in Fig. 18, has the zinc plate suspended between two carbon plates which are joined together at the top. The solution used is made up of dilute sulphuric acid and bichromate of potash. The latter substance chemically unites with the free hydrogen and so prevents polarization. This solution also attacks the zinc, even when the circuit is open, and when not in use the zinc plate is raised above the solution by the rod *A*.

Leclanche Cell. In place of the sulphuric acid solution, this cell is provided with a solution of ammonium chloride (sal-ammoniac), in which a zinc rod is placed. Within the jar containing this solution is placed a porous cup, as shown in Fig. 19. This contains a rod of carbon, which is the inactive element, and closely packed about it is black oxide of manganese and powdered carbon. The oxide slowly gives off oxygen and so prevents

accumulation of hydrogen about the carbon. The porous cup, although it does not interfere with the passage of the current, protects the zinc from the action of the oxide. This cell is much used in connection with telephones and electric bells, or where it is desired to use it for only a few minutes at a time. If used for a long period, the current strength decreases, but quickly regains its original power when the current is interrupted. It is therefore well adapted for intermittent service.

Daniell Cell. The Daniell cell (Fig. 20) is made up of an outer portion of copper, which serves as the inactive element. Within this is a saturated solution of copper sulphate, and crystals

Fig. 19.

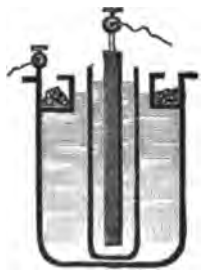


Fig. 20.

of copper sulphate are provided in perforated cups at the top, so that they may dissolve and keep the solution saturated. A porous cup containing dilute sulphuric acid or zinc sulphate and a rod of zinc, completes the cell. The porous cup protects the zinc from the copper sulphate solution, and this solution prevents the hydrogen from accumulating about the copper. The hydrogen unites chemically with the copper sulphate forming sulphuric acid and free copper. The free copper is then deposited upon the outside copper portion. The action is represented as follows:

$$H_2 + CuSO_4 = H_2SO_4 + Cu,$$

which is equivalent to saying that hydrogen united with copper sulphate produces sulphuric acid and copper.

This cell is very constant in its action because, as long as the copper sulphate solution is saturated, no polarization can take place. This cell is much used in telegraphy, and is kept on a closed circuit, the interruption of the circuit being used to give the signals, instead of the closing of the circuit.

Grove Cell. In the Grove cell (Fig. 21) a hollow cylinder of zinc is placed in dilute sulphuric acid. Within this cylinder is a porous cup containing strong nitric acid and a strip of platinum for the inactive element. Polarization is prevented by the hydrogen uniting with the nitric acid. This cell has a low internal resistance and can produce a strong current for several hours.

Bunsen Cell. This is similar to the Grove cell, except that the platinum is replaced by a rod of carbon (Fig. 22). It has a slightly higher electromotive force than the Grove cell and is less expensive, but it has higher internal resistance.

Fig. 21.

Fig. 22.

Gravity Cell. Where one of the two liquids used in a cell is heavier than the other, their difference in specific gravity may be depended upon to keep the liquids separate, instead of using a porous cup. The heavier liquid then remains at the bottom of the cell and the lighter one forms a layer above it. Fig. 23 shows such a cell, which is the same as the Daniell cell except that no porous cup is used. A copper plate at the bottom is surrounded by crystals of copper sulphate and covered with a solution of the same. The zinc is supported above this and in a dilute solution of sulphuric acid or zinc sulphate. The copper sulphate solution being the heavier remains at the bottom and prevents polarization. The two solutions do not remain entirely separated, however, as the heavier solution slowly diffuses upward.

Dry Cell. In this cell, which is more properly called a *moist* cell, the usual liquid solutions are dispensed with, and in place of them the cell is provided with substances capable of retaining

moisture for a long time. These cells have the advantage of being very conveniently handled and are extensively used. One form of dry cell is shown in Fig. 24. In this cell the usual glass jar is replaced by a zinc tube or cup, to which a clamping screw is attached. Within this is a carbon rod forming the inactive plate and also provided with a clamping screw. The zinc is lined with a compound corresponding to the acid solution of other cells, and the carbon is surrounded by a semi-solid compound which acts to prevent polarization. After the ingredients have been placed in the cell, it is sealed at the top with bitumen or other similar substances.

MAGNETIC EFFECTS OF ELECTRIC CURRENT.

On the preceding pages magnetism, static charges of electricity and the electric current have been considered. It has been shown that static charges act very much like magnets in regard to attraction, repulsion, induction, etc.; but no connection between magnets and charges of electricity has yet been discovered. A static charge, either positive or negative, has the same effect upon the north pole of a magnet as upon the south pole. There is, however, a close relation between magnetism and the electric current.

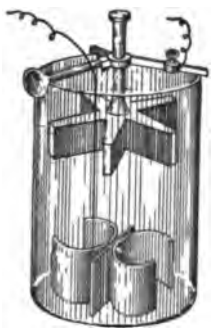


Fig. 23.

Deflection of the Magnetic Needle. We have seen that when a conductor connects two materials having a difference of potential between them, that a current will flow as soon as the circuit is completed. This current causes the wire to be surrounded by a magnetic field, and the magnetic field consists of lines of force which encircle the conductor. The field is strongest near the conductor and diminishes gradually in strength at increasing distances therefrom. The presence of this magnetic field may be shown by the experiment illustrated in Fig. 25. When the pivotally supported magnet having poles N and S is placed near the wire carrying a current, the needle will be deflected and tend to place itself at right angles to the wire. The direction in which the needle is deflected will depend upon the direction of the

current, and whether the needle is above or below the wire. The amount of the deflection will depend mainly upon the current strength, length of the magnet and strength of its poles. This phenomenon is made use of in measuring the strength of currents, and is one of the fundamental principles of electrical measuring instruments.

Fig. 24.

Solenoid. When an electric current is passed through a coil of wire such as is shown in Fig. 26, the coil becomes equivalent to a magnet, and has poles *N* and *S* as indicated. Such a coil is called a solenoid. The magnetic field surrounding each turn of wire unites to form a magnetic field about the coil similar to that of a bar magnet, as shown in Fig. 3. If free to turn, the solenoid assumes a position such that its axis will point north and south, and thus acts like a compass needle. The same phenomena of attraction and repulsion exist between solenoids, or between solenoids and magnets, as exist between magnets. Which end of the solenoid becomes the north pole and which the south, depends upon the direction of the current through the coil.

Electromagnets. Since a solenoid is surrounded by a magnetic field similar to that of a magnet, it follows that the solenoid is capable of magnetizing pieces of soft iron and attracting them in the same way as does a steel magnet. The field of a solenoid is strongest within its windings, and it follows that if a bar of soft iron is placed within the coil, the bar will be much more strongly magnetized than if placed in any other position about the coil. A coil adapted to carry a current and provided with a soft iron core is called an *electromagnet.* In order to permit the wire to be closely wound and at the same time force the current through each turn, the wire is covered with insulation throughout its length. Such insulation may consist of a covering of silk, cotton or guttapercha. The core remains a magnet only while the current is flowing.

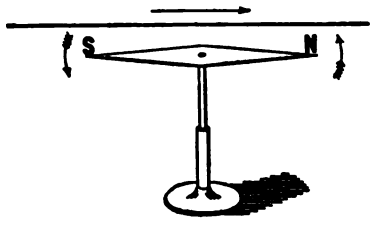


Fig. 25.

Electromagnets may be made very powerful, and when made in the form of a horseshoe have great lifting power. A horseshoe electromagnet is shown in Fig. 27. The winding of the two coils *A* and *B* must be such that the ends of the horseshoe have opposite polarity. This condition is fulfilled if the winding

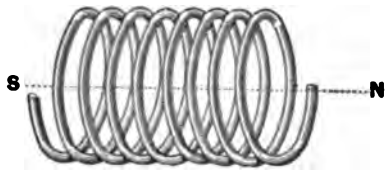


Fig. 26.

on the two links is in the same direction, when the horseshoe is straightened out.

Applications of Electromagnets. The great advantage in using the electromagnet lies in the control of its magnetism. When the current is passing, the core is strongly magnetized, and when no current flows it ceases to act as a magnet. Hence its action may be controlled by simply opening or closing the circuit by a key or switch, the source of the electricity being included in the circuit. This control of the magnet may be accomplished at great distances by merely extending the wires from the coil to the distant point and operating the switch or key at that point.

Fig. 27.

Telegraphic instruments are constructed upon this principle, the closing of a key at a distant point causing the electromagnet to attract a piece of iron called its armature, supported near its poles, and so give a signal. When the current ceases to flow, the armature is forced away from the poles by the action of a spring, the force of the spring being overcome, however, whenever the current passes.

The electromagnet is also used in electric bells. The armature carries a hammer which strikes against the bell whenever the armature is attracted. By the rapid opening and closing of the circuit, which is accomplished automatically, the hammer is made

to strike the bell repeatedly. Electric clocks are also governed by the action of electromagnets.

PRODUCTION OF CURRENTS BY INDUCTION.

We have seen that magnets may induce magnetism in pieces of soft iron and attract them. We have also seen that electric charges may induce charges in other bodies. Induced *currents* may be produced by the relative movement of a magnetic field and a neighboring conductor, or by the action of a current in one conductor upon a neighboring conductor. The production of

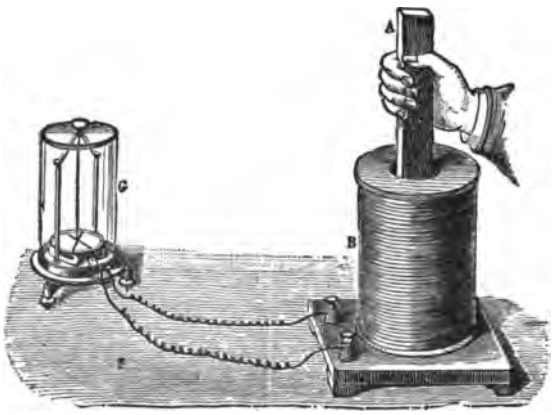


Fig. 28.

induced currents is therefore a very different phenomenon from that of induced static charges.

Induction by Magnets. Fig. 28 represents a coil *B*, having connected in its circuit an instrument *G* for the purpose of indicating the presence of any current. The magnet *A* is adapted to be thrust within the coil. Upon forcing the magnet rapidly within the coil, the instrument will show that a momentary current passes. The current continues as long as the magnet is in motion, and ceases as soon as the magnet is brought to rest. The quicker the magnet moves the greater is the strength of the induced current. Upon withdrawing the magnet a current is also induced, and this flows in the opposite direction to the former current.

These induced currents are caused by the field surrounding the magnet moving or cutting across the wires composing the coil. If a current were passed through the coil, it would create a magnetic field, so on the other hand, the movement of a magnetic field within the coil produces a current. It makes no difference whether the magnet or the coil is moved, so long as there is relative movement. This production of a current by the relative movement of a magnetic field and a conductor, is the fundamental principle of all dynamos.

Fig. 29.

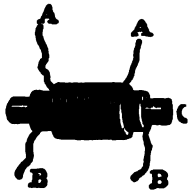
Induction by Currents. As a solenoid is surrounded by a magnetic field similar to that of a bar magnet, it follows that if a solenoid carrying a current were thrust within another coil, induced currents would be produced in the latter. This experiment is illustrated in Fig. 29. These induced currents, as in the case when the magnet is used, only flow during the motion of the solenoid. When the solenoid is inserted, the induced current flows in one direction and when withdrawn, it flows in the opposite direction. The insertion of the solenoid induces a current which has a direction opposite to that in the solenoid, and the withdrawal induces a current which has the same direction as that in the solenoid.

Induction Coil. Suppose now that the two coils shown in Fig. 29 are placed one within the other, there being no current passing, and that a current is afterwards passed through the inner coil. Upon permitting the passage of a current in the inner coil a momentary current is induced in the outer coil, the same as if a magnet had been thrust into the coil. This induced current continues, however, only while the current in the inner coil is increasing in value from zero to its normal amount. As soon as this normal strength is reached the induced current ceases to flow. Now when the circuit of the inner coil is broken and its current ceases to flow, another momentary current is induced in the outer coil, which has a direction opposite to that formerly passed

through it. Such an instrument for producing induced currents is called an *induction coil.* The coil through which the original current is passed is called the *primary* coil, and that in which the currents are induced is called the *secondary* coil. The induction coil is the fundamental principle of transformers, commonly used in long distance power transmission.

Fig. 30 illustrates an induction coil having the two sets of windings *A* and *B* and also supplied with a soft iron core *C*. This iron core greatly increases the amount of induction.

The production of induced currents by opening and closing, or making and breaking the primary circuit, is similar in action to thrusting a magnet within and withdrawing it from a coil. When a magnet is used, the induction is caused by the magnetic



A is secondary coil.
B is primary coil.

Fig. 30.

field moving across the wire composing the coil. Now when the primary circuit is closed, a magnetic field is created, which is equivalent to thrusting a magnet within the coil. The breaking of the primary circuit is equivalent to withdrawing the magnet, and so induces a current. The current induced by closing the primary circuit is *opposite* in direction to that of the primary current, and that induced by breaking the primary circuit is in the *same* direction as the primary current. The induced currents are only caused by the changing in strength of the magnetic field surrounding the secondary circuit. Therefore, while a constant current is passing in the primary circuit, there will be no induced currents. When the strength of the primary current changes, however, secondary currents will be induced. The strength of these induced currents will depend upon the abruptness of change in the primary current, and their direction will depend upon whether the primary current increases or decreases.

It should be remembered that before a current can flow there

must be a closed circuit, and an electromotive force. A current flows in the secondary circuit only when it is closed, but the electromotive force exists whether or not the secondary circuit is closed. Strictly speaking the electromotive force is first produced or generated, and the current then flows when the circuit is closed. The value of the electromotive force generated in the secondary, depends upon the number of turns in the same; a much higher electromotive force being generated in a coil of a large number of turns than in a coil of a few turns. This fact is of great practical importance, for it thus provides a means of obtaining very high electromotive forces.

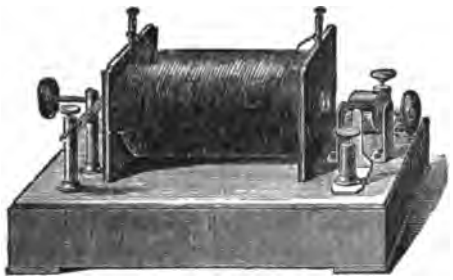


Fig. 31.

Fig. 31 illustrates an induction coil arranged to generate a very high electromotive force, and for producing sparks between widely separated points. The primary coil consists of a few turns of coarse wire, and about this is the secondary coil made up of many thousand turns of fine wire, all of which are well insulated. In the primary circuit are connected a few Grove's or Bunsen's cells and a switch for interrupting the circuit. The making and breaking of the primary circuit generates a very high electromotive force in the secondary. Sparks of considerable length may be produced between the terminals of the secondary by this type of coil. A condenser is used in connection with the device, in order to decrease the electromotive force induced by closing the primary circuit, and to increase that induced by opening the primary circuit. The sparking therefore occurs at the breaking of the primary circuit. A powerful induction coil made at London, in which the secondary coil contained 280 miles of wire wound in 340,000 turns, yields a spark 42½ inches in length, when worked by 30 Grove's cells.

Mutual and Self-Induction. Induction produced in one conductor by currents in another, which has no electrical connection with the first, is called *mutual* induction. We have seen

that mutual induction is caused by the change in strength of the magnetic field surrounding the secondary coil. The primary coil must necessarily be subject to the same change in field strength, which is therefore acted upon inductively as well as the secondary coil. This reaction tends to oppose any increase or decrease in the primary current. It is greater for a coil having a large number of turns or one provided with an iron core. This inductive action of a coil upon itself is called *self-induction.* Electromagnets have very high self-induction. Upon closing the circuit in such a coil its self-induction causes the current to increase in strength very slowly, and upon opening the circuit self-induction tends to prolong the current, and produces what is termed an "extra current." The high electromotive force causing this extra current, may be sufficient to give a dangerous shock, and produces a bright spark where the circuit is opened.

HEATING EFFECTS OF CURRENT.

Heating Depends upon Resistance. We have seen that some substances are very good conductors of electricity, that others are fairly good and that others are very poor conductors. That is, some substances offer very much more resistance to the flow of electricity than others. In order to force the current through this resistance, a certain amount of energy must be expended and the greater the resistance, the greater is the amount of energy required. The energy which is thus consumed, appears in the form of heat. From every part of a circuit through which a current is flowing, heat is dissipated, and this heating raises the temperature of the circuit a certain amount. A short, stout copper wire has low resistance, and so causes but little heat to be generated. Also on account of its large radiating surface, this heat is readily given off to the surrounding air, and therefore its temperature is raised only to a small extent. A fine platinum wire, however, has high resistance and but small radiating surface, hence if the same current be passed through this wire, it will come to a high temperature and may even become incandescent.

The laws of heating in electrical circuits were first formulated by Joule. Joule's law is as follows:

The number of heat units developed in a conductor is propor-

tional to its resistance, to the square of the current, and to the time that the current lasts.

The amount of heat developed therefore increases in direct proportion to the resistance, but increases as the *square* of the current. Hence doubling the resistance, doubles the heat generated, if the current remains the same, but doubling the current increases the generation of heat four fold with the same resistance.

Applications. The heating of a wire carrying a current is made use of for lighting purposes, and again for blasting, exploding sub-marine mines, etc. Conducting wires are run from the explosive material to a distant point, and include a battery and

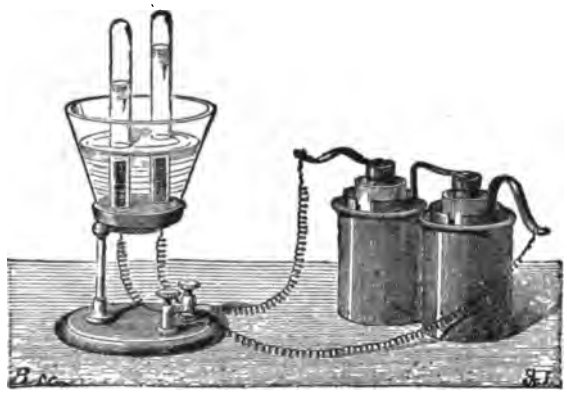


Fig. 32.

piece of fine platinum wire in the circuit. Some combustible substance is placed around the platinum, and serves to ignite the main charge when the platinum wire is heated. Upon closing the circuit this wire becomes hot and the explosion takes place.

This principle of heating is also applied to *fuses*, used for the protection of electric lighting or power circuits. The fuse consists of an easily fusible metal which is inserted in the circuit. The passage of an excessive or dangerously large current heats the fuse to its melting point and so breaks the circuit. The cause of the large current may then be removed and a new fuse inserted in place of the old one.

Electric welding is accomplished by passing a powerful cur-

rent through two rods held together. The heating at the junction softens the metal and the rods become welded.

The electrical heating of cars and of cooking utensils is accomplished by passing a current through wires of high resistance.

Thermo-Electric Currents. If the junction of two dissimilar metals forming part of a circuit, is heated, a current is produced. If a piece of bismuth and a piece of antimony be soldered together and form part of a circuit, then if the junction be heated to a temperature higher than that of the rest of the circuit, a current will flow in the direction from bismuth to antimony through the heated section. If the junction be cooled below the temperature of the rest of the circuit, a current will flow in the opposite direction. The current will continue to flow as long as the difference in temperature is maintained. Currents thus produced are called *thermo-electric* currents. This phenomenon is commonly known as the Seebeck effect from the name of its discoverer.

About the only application of the above phenomenon is made to instruments for detecting very slight differences in temperature. These are arranged so that a very small rise in temperature of a bismuth and antimony junction, will generate a current which may be measured by a sensitive instrument in the circuit. Other metals may be used but the effect is not nearly so pronounced.

CHEMICAL EFFECTS OF CURRENTS.

Electrolysis. When a current of electricity is passed through water from one terminal of a circuit to the other, the water is decomposed into its constituent parts, hydrogen and oxygen. The hydrogen gas rises in bubbles from one terminal and the oxygen gas from the other. Fig. 32 illustrates an arrangement of apparatus by which this decomposition may be attained, and by which the gases may be separately collected. The current from a couple of cells is conducted through one wire to a vessel containing water, then through the liquid and through the other wire to the cells. Pure water is a poor conductor, and a few drops of sulphuric or hydrochloric acid are added to increase its conductivity. The two terminals project through the bottom of the vessel and over each of them is placed a tube closed at the upper

end and filled with water. The gas given off from each terminal rises and collects in the upper portion of the tubes. Oxygen rises from the terminal by which the current enters the liquid and hydrogen from the terminal by which it leaves. Oxygen is therefore collected in one tube and hydrogen in the other. Two volumes of hydrogen and one volume of oxygen unite to form water, and hence in its decomposition the volume of hydrogen collected is twice that of the oxygen.

Other liquids may be decomposed by passing a current through them, and this process of decomposition is called *electrolysis*. Liquids which may be decomposed in this manner are called *electrolytes*. The terminals by which the current enters and leaves the liquid are called *electrodes*. The *anode* is that terminal by which the current enters and the *kathode* is that by which it leaves the liquid.

Some liquids such as oil, which is an insulator, and mercury which is itself an element, cannot be decomposed by an electric current. Dilute acids however, and solutions of metallic salts are readily decomposed.

For an example of the decomposition of a salt we will take a solution of copper sulphate for the electrolyte. The current from a single cell is sufficient to decompose this salt. By passing the current through the liquid, metallic copper is separated from its compound and is deposited in a pure state upon the kathode. The remainder of the compound unites with the water to form sulphuric acid and oxygen. The latter rises in bubbles from the anode. The final result therefore, is that the kathode receives a coating of pure copper and the liquid becomes dilute sulphuric acid. If the anode consists of copper, it will dissolve into the liquid forming copper sulphate as fast as the pure copper is deposited upon the kathode. In this case the action of the current is to transfer the copper from the anode to the kathode.

The amount of chemical action in an electrolytic cell depends upon the strength of current, and the time it continues.

Electrotyping. The decomposition of salts by the electric current has received a most important application in *electrometallurgy*. By this process exact reproductions may be made of type, plaster casts, medals, etc. In the usual process a wax mould

of the object is first made, and this is coated with graphite or powdered bronze to render it a good conductor. The mould is then suspended in, and forms the kathode of an electrolytic cell. For the formation of a copper electrotype, the anode is a plate of copper and the electrolyte is copper sulphate. The passage of the current produces an exact reproduction of the original object on the wax mould. Even the faintest lines are accurately reproduced.

Electroplating. By this process the cheaper metals may receive a thin coating of gold, silver, nickel, etc. The objects to be plated are suspended in the electrolytic cell and form the kathode. In electro-gilding the electrolyte is a solution of double cyanide of gold and potassium, and a plate of gold forms the anode. This plate dissolves into the liquid as fast as the gold coating is deposited upon the objects to be coated. For electro-silvering a double cyanide of silver and potassium and a plate of silver are used. Iron objects are usually coated with a copper deposit before being gilded, silvered or nickeled. The copper presents a better surface for the other metals and gives more durable results.

Accumulators, also called storage or secondary batteries, consist of cells which are capable of giving out electrical energy, in virtue of the chemical change caused by first passing a current through them from an external source.

The simplest type of accumulator is called the Planté battery from the name of its inventor. This cell consists simply of lead plates in dilute sulphuric acid. The plates are "formed" or made active by repeatedly "charging" and "discharging" the cells. That is, a current from an outside source is passed through the cell from one plate to the other, and then by connecting the plates by a wire a current will flow until the potential of each plate is the same. By repeated charging and discharging, the capacity of the cell is greatly increased. No electricity is stored up by the plates as with the Leyden jar, but the effect is due entirely to a chemical change on the surface of the plates. By repeated chargings this chemical change penetrates deeper and deeper into the plates and thus increases their capacity. The current received from the cell flows in an opposite direction to that by which the cell is charged.

The exact chemical change produced on the plates is not yet fully determined. The charging action is believed to consist mainly in the formation of peroxide of lead ($Pb\ O_2$) on the positive, and metallic lead (Pb) on the negative plate, which is converted into lead oxide (Pb O) on both plates by the discharge.

A serious objection to the Planté battery is the great length of time required to first form the plates. In order to hasten this forming process, the plates may first be mechanically roughened, thus increasing their exposed surface and porosity. Treating the plates with dilute nitric acid also hastens the forming process. After the plates have finally received a suitable coating of active material, the cells are enabled to produce considerable electrical energy after being once charged.

Fig. 33.

In the Faure type of accumulator, the long time required for forming the plates is largely overcome by pasting the lead oxide, or active material, directly upon the plates. An accumulator of this type is shown in Fig. 33. Several plates are used in order to increase the capacity of the cell, the alternate plates being connected together and so being equivalent to two large plates. Each plate is made up of a leaden grid cast in an iron mould, and the openings are filled with the paste. This type of accumulator has the objection that the paste may become loose, so that it fails to make good contact with the grid, or falls off in fragments. The Planté type is usually the more expensive to make and is more durable.

A large number of accumulators have been devised in which one or both of the lead plates are replaced by some other metal. In one such form the negative plate is made of zinc instead of lead. This has the advantage of a slightly higher electromotive force, and permits a considerable reduction in weight. A difficulty with this type of cell is the formation of scale on the zinc plate during the charging process, which is likely to fall off or lodge between the plates and so render them useless. Another diffi-

culty is that the density of the solution varies between the top and bottom of the plates, which causes a difference in the amount of action at different portions of the plates.

Accumulators are now much used in electric motor vehicles, the cells being recharged after the vehicle has been used a certain length of time.

THE TELEPHONE.

The telephone presents a very ingenious application of the production of currents by induction.

Fig. 34 illustrates a sectional view of the telephone invented by Dr. Graham Bell. It consists essentially of a wooden case within which is placed a long steel magnet *M*. Around one end

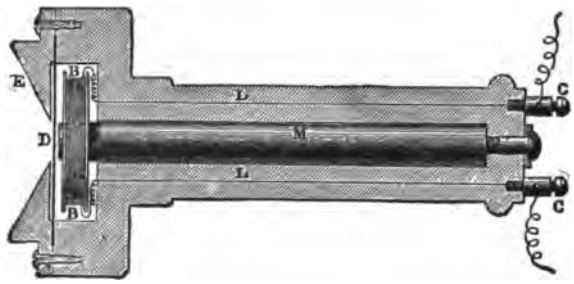


Fig. 34.

of the magnet is placed a coil *B* of fine insulated copper wire, the ends of which pass through passages *L L* in the case, and are attached to binding screws *C C*. At a slight distance from one end of the magnet is supported a flexible disc *D* of soft iron. The disc is directly opposite the opening in the mouthpiece *E*, and arranged to vibrate in accordance with the vibrations of the air as produced by the speaker. From the binding screws, wires extend to a similar instrument, which is held to the ear of a person at some distance away. The instrument spoken into is called the *transmitter* and that from which the sounds are received is called the *receiver*. Each instrument may be used for both transmitting and receiving, but it is more convenient for each operator to have one instrument for transmitting and another for receiving.

The action of the instrument depends upon the fact that whenever the relative position of a magnet and a coil of wire is

changed, an electric current is produced in the coil. This phenomenon is described on pages 29 and 30.

In the telephone, the change in strength of magnetic field within the coil *B* is caused by vibrations of the disk *D*, such vibrations being produced when the mouthpiece is spoken into. The disk being of soft iron is magnetized by the magnet *M*. Now when the disk is near the magnet, the field passing through the coil is stronger than when the disk is at a slightly greater distance therefrom. It therefore follows that when the disk approaches the magnet, the field strength is increased and when it recedes from the magnet, the field is decreased. This change in field produces currents in the coil and its circuit, which change in strength and direction in accordance with the vibrations of the disk. These currents are transmitted through the circuit to the coil of the distant instrument, and momentarily increase or decrease the strength of the magnet. When the current in the coil is in such a direction as to strengthen the magnet, the iron disk is caused to approach the magnet; and when the current is in such a direction as to weaken the magnet, the disk is caused to recede. Hence, the movement of the receiving disk corresponds to that of the transmitting disk, and produces the same vibrations of the air and so reproduces the sound.

The vibration of the receiving disk is similar to that of the transmitting disk, but the sound produced is considerably enfeebled. The action is not due to a series of sharp and disconnected changes, but in each of the momentary currents there is a gradual rise and fall, corresponding to every gradation and inflection of the air produced by the speaker. The amount of vibration of the disk is extremely small as well as the currents produced. It is now the practice to use the Bell type of telephone as the receiver only, and to use a different form of instrument for the transmitter together with a battery. The action of this transmitter depends upon the principle that if the resistance of a circuit is increased, the current will be decreased, and if the resistance is decreased, the current will be increased so that when the telephone receiver is connected in circuit with the battery the slightest change in resistance, caused by the vibrations of the transmitter disk, will cause the receiver disc to vibrate correspondingly.

THE TELEGRAPH.

Having considered the electromagnet and the effect produced in a core of soft iron, by a current of electricity which passes through a coil of insulated wire surrounding it, we are prepared to apply these principles to the electric telegraph.

Various devices have been tried, with more or less success, for transmitting and recording signals from one point to another.

The apparatus used in one of these early attempts caused sparks from Leyden jars to pass through a circuit. Another was operated by means of a galvanometer needle which was deflected to the right or left.

None of these attempts were of any practical value except that they served to lead up to the telegraph of the present day. There are now two successful methods of operating telegraph lines; namely the "Open Circuit" and the "Closed Circuit" systems. The former is used in Europe and its chief advantage is that no energy is consumed from the batteries except when signals are actually being transmitted. The latter system which is used almost entirely in America, has on the other hand, advantages which offset this. On account of its greater importance in this country we will consider more in detail the "Closed Circuit" system.

In its simplest form this system consists of three principal parts connected in series in the circuit:

1. A key for transmitting the signals.
2. An instrument for receiving these signals.
3. A battery which furnishes the current to operate it.

The Morse Sounder. The instrument most commonly used for receiving the signals is the Morse sounder, shown in Fig. 35. It consists essentially of an inverted electromagnet E of the horseshoe type. This electromagnet differs somewhat from the one shown in Fig. 27, in that it is made up of two cores and a yoke or back strap B in order to furnish a better bearing for the electromagnet upon its base than would be possible with one having a rounding back. Above the poles of this magnet, an armature A of soft iron is attached to a pivoted lever L of non-magnetic material, which is controlled by a spring S. When a current

passes through the coils of this electromagnet, the cores become magnetized and attract the armature downward. Just before it touches the poles of the electromagnet however, the lever to which it is attached, strikes a metallic stop F and a click is heard. When the current ceases to flow, the cores of the electromagnet

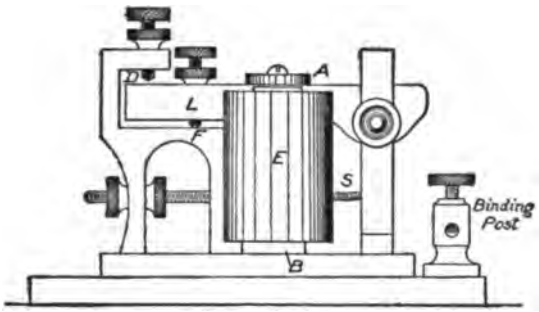


Fig. 35.

lose their attractive force. The armature is then carried upward by means of the spring which acts on the lever to which the armature is attached. The lever then strikes against another stop D and another click is heard. The range of stroke or play of the lever is adjusted by set screws.

AMERICAN MORSE CODE.

A ·—	J —·—·	S ···	2 ··—··
B —···	K —·—	T —	3 ···—·
C ·—·—	L ——	U ··—	4 ····—
D —··	M ——	V ···—	5 —————
E ·	N —·	W ·——	6 ·····
F ··—·	O ··	X —··—	7 ——···
G ——·	P ·····	Y ·—·—	8 —····
H ····	Q ··—·	Z —···	9 —··—
I ··	R ·—·	1 ·———·	0 ———

If the duration of time of current flow is very short, the interval of time between these two clicks will be correspondingly short. The signal in this case would be a "dot." If the interval between the two clicks be longer, the signal would be a dash.

In this manner by a telegraphic code, consisting of different signals made up of dots, spaces and dashes for all the letters of the alphebet and numbers, it is possible to send and receive messages. Beside the "Sounder" described above in which the

receiving operator depends entirely upon sound for the message, there are also in use the "Embosser" and the "Ink Writer."

In the first a sharp point attached to the armature lever cuts the dots or dashes in a strip of paper moved past it by clock work; in the second the dots and dashes are recorded on the moving paper by an inked wheel. These last two methods are, however, little used by expert operators.

The Morse Key. The Morse Key or instrument by which the signals are controlled is shown in Fig. 36.

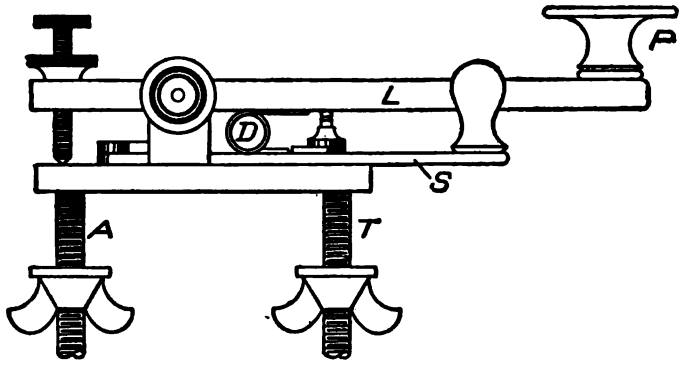


Fig. 36.

It is composed of a pivoted lever L fitted at one end with a circular plate P on which the fingers of the operator rest. The key is secured to the base by two thumb screws A and T, to which the terminals of the circuit are attached. The screw A is in electrical connection with the main body of the key, including the lever. The screw T is insulated from the rest of the key by some non-conducting material, and terminates in a platinum point.

On the under side of the lever and immediately above this point is another platinum tip which, when the lever is pressed down, makes contact, thus completing the circuit through the key.

The lever is kept in proper position when not in use, by a spring D and the length of its stroke is controlled by an adjustable set screw. A switch S, for closing the circuit when the instrument is not in use, completes this piece of apparatus.

The Battery. The battery used for operating the circuit is either the Daniell cell shown in Fig. 20 or the Gravity cell shown in Fig. 23. In the "Closed Circuit" system the batteries are

required to furnish current nearly all the time and these cells are remarkably well adapted for this purpose as they do not polarize and require very little attention other than keeping them supplied with copper sulphate and removing the zinc sulphate.

The number of cells used depends upon the length of the line and resistance of the instruments in the circuit.

In actual practice there is a key and sounder at every station on the line, all being connected in series together with a sufficient number of cells to furnish the current. The switches of all the keys being closed, a current will flow through the electromagnets of all the sounders.

When an operator wishes to communicate with a certain station, he opens the switch of his key, thus breaking the circuit and he can then by means of the lever, call the station and send any message he desires over the line. This message will, of course be simultaneously signalled by all the sounders on the circuit.

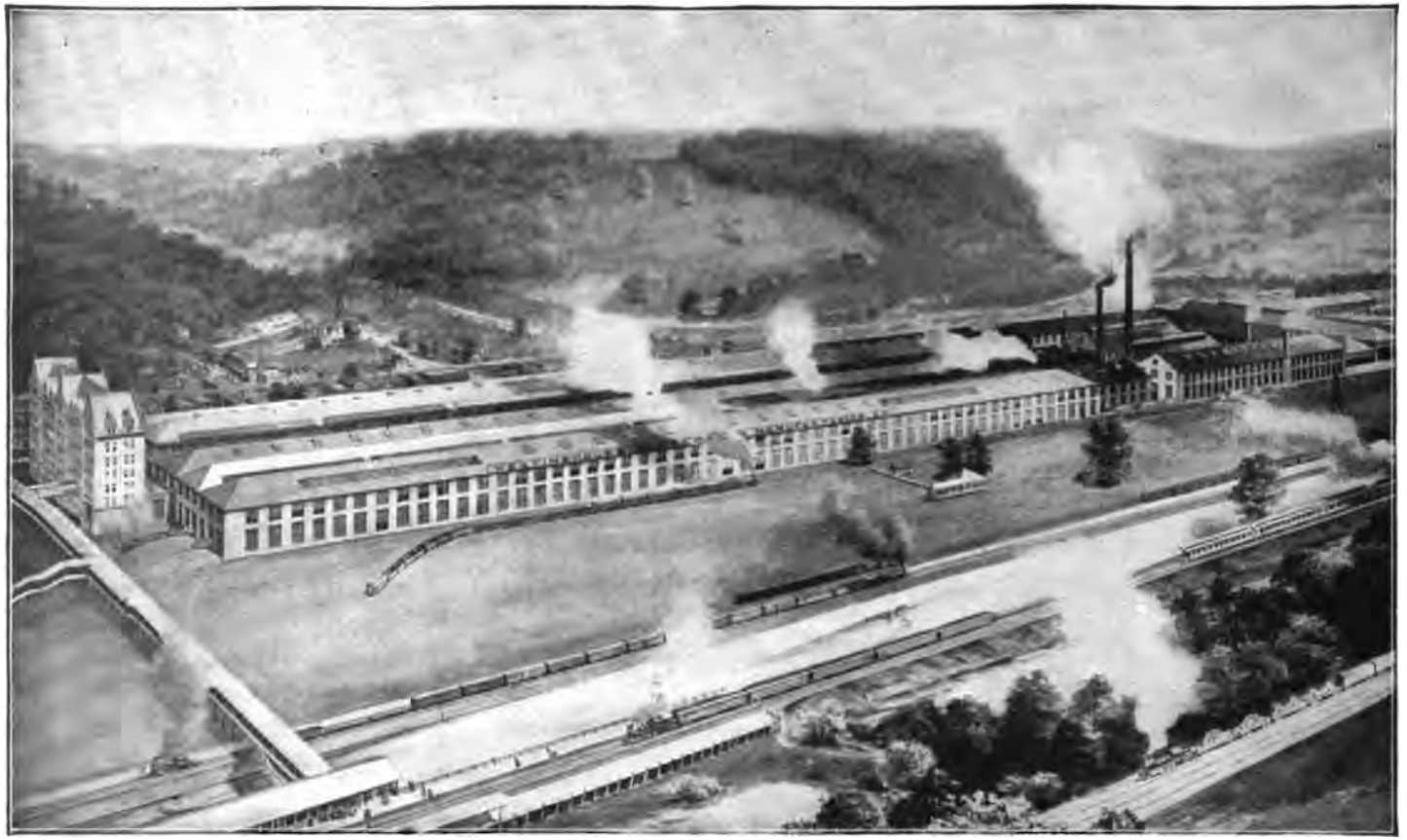
When the operator finishes his message he closes the switch and is then prepared to receive the reply.

The Relay. In the case of long lines having many instruments in series, the main current would not be strong enough to properly operate the receiving sounder directly, and the relay is then resorted to.

This instrument consists of a horizontal electromagnet, having a large number of turns in its coils, in series with the main line. It has an armature somewhat like that of the sounder already described. It is however more delicately balanced so that less magnetic force is required to attract it.

When the line current flows through the relay, this armature is drawn against its stop, and thus it makes contact for a local circuit including a Morse sounder and sufficient batteries to work it.

In this manner, the main or line current, although not strong enough to operate the sounder directly, can be made to control the sounder in the local circuit, by means of the relay.



A REPRESENTATIVE AMERICAN ELECTRICAL MANUFACTURING PLANT (Westinghouse)

SECTION 2.

THE ELECTRIC CURRENT.

Electromotive Force. When a difference of electrical potential exists between two points, there is said to exist an *electromotive force*, or tendency to cause a current to flow from one point to the other. In the voltaic cell one plate is at a different potential from the other, which gives rise to an electromotive force between them. Also in the induction coil, an electromotive force is created in the secondary circuit caused by the action of the primary. This electromotive force is analogous to the *pressure*, caused by a difference in level of two bodies of water connected by a pipe. The pressure tends to force the water through the pipe, and the electromotive force tends to cause an electric current to flow.

The terms potential difference and electromotive force are commonly used with the same meaning, but strictly speaking the potential difference gives rise to the electromotive force. Electromotive force is commonly designated by the letters *E. M. F.* or simply *E.* It is also referred to as *pressure* or *voltage*.

Current. A current of electricity flows when two points, at a difference of potential, are connected by a wire, or when the circuit is otherwise completed. Similarly water flows from a high level to a lower one, when a path is provided. In either case the flow can take place only when the path exists. Hence to produce a current it is necessary to have an electromotive force and a closed circuit. The current continues to flow only as long as the electromotive force and closed circuit exist.

The strength of a current in a conductor is defined as the quantity of electricity which passes any point in the circuit in a unit of time.

Current is sometimes designated by the letter *C*, but the letter *I* will be used for current throughout this and following sections. The latter symbol was recommended by the International Electrical Congress held at Chicago in 1893, and has since been universally adopted.

Resistance. Resistance is that property of matter in virtue of which bodies oppose or resist the free flow of electricity. Water passes with difficulty through a small pipe of great length or through a pipe filled with stones or sand, but very readily through a large clear pipe of short length. Likewise a small wire of considerable length and made of poor conducting material offers great resistance to the passage of electricity, but a good conductor of short length and large cross section offers very little resistance.

Resistance is designated by the letter *R*.

Volt, Ampere and Ohm. The *volt* is the practical unit of electromotive force.

The *ampere* is the practical unit of current.

The *ohm* is the practical unit of resistance. The *microhm* is one millionth of an ohm and the *megohm* is one million ohms.

The standard values of the above units were very accurately determined by the International Electrical Congress in 1893, and are as follows:

The International ohm, or true ohm, as nearly as known, is the resistance of a uniform column of mercury 106.3 centimeters long and 14.4521 grams in mass, at the temperature of melting ice.

The ampere is the strength of current which, when passed through a solution of silver nitrate, under suitable conditions, deposits silver at the rate of .001118 gram per second. Current strength may be very accurately determined by electrolysis, and it is used therefore in determining the standard unit.

The volt is equal to the E. M. F. which, when applied to a conductor having a resistance of one ohm, will produce in it a current of one ampere. One volt equals $\frac{1000}{1434}$ of the E. M. F. of a Clark standard cell at 15° Centigrade.

RESISTANCE.

All substances resist the passage of electricity, but the resistance offered by some is very much greater than that offered by others. Metals have by far the least resistance and of these, silver possesses the least of any. In other words, silver is the best conductor. If the temperature remains the same, the resistance of a

conductor is not affected by the current passing through it. A current of ten, twenty or any number of amperes may pass through a circuit, but its resistance will be unchanged with constant temperature. Resistance is affected by the temperature and also by the degree of hardness. Annealing decreases the resistance of a metal.

Conductance is the inverse of resistance; that is, if a conductor has a resistance of R ohms, its conductance is equal to $\frac{1}{R}$.

Resistance Proportional to Length. The resistance of a conductor is directly proportional to its length. Hence, if the length of a conductor is doubled, the resistance is doubled, or if the length is divided, say into three equal parts, then the resistance of each part is one third the total resistance.

Example. — The resistance of 1283 feet of a certain wire is 6.9 ohms. What is the resistance of 142 feet of the same wire?

Solution. — As the resistance is directly proportional to the length we have the proportion,

$$\text{required resistance} : 6.9 : : 142 : 1283$$

or,
$$\frac{\text{required resistance}}{6.9} = \frac{142}{1283}$$

Hence,
$$\text{required resistance} = 6.9 \times \frac{142}{1283}$$
$$= .76 \text{ ohm (approx.)}$$

Ans. .76 ohm.

Example. — The resistance of a wire having a length of 521 feet is .11 ohm. What length of the same wire will have a resistance of .18 ohm?

Solution. — As the resistance is proportional to length, we have the proportion,

$$\text{required length} : 521 : : .18 : .11$$

or,
$$\frac{\text{required length}}{521} = \frac{.18}{.11}$$

Hence,
$$\text{required length} = 521 \times \frac{.18}{.11}$$
$$= 852 \text{ feet (approx.)}$$

Ans. 852 feet.

Resistance Inversely Proportional to Cross-Section. The resistance of a conductor is inversely proportional to its cross-sectional area. Hence the greater the cross-section of a wire the less is its resistance. Therefore, if two wires have the same length, but one has a cross-section three times that of the other, the resistance of the former is one-third that of the latter.

Example. — The ratio of the cross-sectional area of one wire to that of another of the same length and material is $\frac{257}{101}$. The resistance of the former is 16.3 ohms. What is the resistance of the latter?

Solution. — As the resistances are inversely proportional to the cross-sections, the smaller wire has the greater resistance, and we have the proportion:

$$\text{required resist.} : 16.3 :: 257 : 101$$

or,
$$\frac{\text{required resist.}}{16.3} = \frac{257}{101}$$

Hence,
$$\text{required resist.} = 16.3 \times \frac{257}{101}$$
$$= 41.5 \text{ ohms (approx.)}$$

Ans. 41.5 ohms.

Example. — If the resistance of a wire of a certain length and having a cross-sectional area of .0083 square inch is 1.7 ohms, what would be its resistance if the area of its cross-section were .092 square inch?

Solution. — Since increasing the cross-sectional area of a wire decreases its resistance, we have the proportion,

$$\text{required resist.} : 1.7 :: .0083 : .092$$

or,
$$\frac{\text{required resist.}}{1.7} = \frac{.0083}{.092}$$

Hence,
$$\text{required resist.} = 1.7 \times \frac{.0083}{.092}$$
$$= .15 \text{ ohm (approx.)}$$

Ans. .15 ohm.

As the area of a circle is proportional to the square of its diameter, it follows that the resistances of round conductors are inversely proportional to the squares of their diameters.

Example. — The resistance of a certain wire having a diam.

eter of .1 inch is 12.6 ohms. What would be its resistance if the diameter were increased to .32 inch?

Solution. — The resistances being inversely proportional to the squares of the diameters, we have,

$$\text{required resist.} : 12.6 :: .1^2 : .32^2$$

or,
$$\frac{\text{required resist.}}{12.6} = \frac{.1^2}{.32^2}$$

Hence,
$$\text{required resist.} = 12.6 \times \frac{.1^2}{.32^2}$$
$$= \frac{12.6 \times .01}{.1024}$$
$$= 1.23 \text{ ohms (approx.)}$$

Ans. 1.23 ohms.

Specific Resistance. The specific resistance of a substance is the resistance of a portion of that substance of unit length and unit cross-section at a standard temperature. The unit commonly used is the centimeter or inch, and the temperature that of melting ice. The specific resistance may therefore be said to be the resistance (usually stated in microhms) of a centimeter cube or inch cube at the temperature of melting ice. If the specific resistances of two substances are known then their relative resistance is given by the ratio of the specific resistances.

Conductivity is the reciprocal of specific resistance.

Example. — A certain copper wire at the temperature of melting ice has a resistance of 29.7 ohms. Its specific resistance (resistance of 1 centimeter cube in microhms) is 1.594, and that of platinum is 9.032. What would be the resistance of a platinum wire of the same size and length of the copper wire, and at the same temperature?

Solution. — The resistance would be in direct ratio of the specific resistances, and we have the proportion:

$$\text{required resist.} : 29.7 :: 9.032 : 1.594$$

Hence,
$$\text{required resist.} = 29.7 \times \frac{9.032}{1.594}$$
$$= 168. \text{ ohms (approx.)}$$

Ans. 168. ohms.

Calculation of Resistance. From the preceding pages it is evident that resistance varies directly as the length, inversely as

the cross-sectional area, and depends upon the specific resistance of the material. This may be expressed conveniently by the formula,

$$R = s\frac{L}{A}$$

in which R is the resistance, L the length of the conductor, A the area of its cross section, and s the specific resistance of the material.

Example.— A telegraph relay is wound with 1,800 feet of wire .010 inch in diameter, and has a resistance of 150 ohms. What will be its resistance if wound with 400 feet of wire .022 inch in diameter?

Solution.— If the wires were of equal length, we should have the proportion,

$$\text{Required resistance} : 150 :: (.010)^2 : (.022)^2$$

or, $$\text{Required resistance} = 150 \times \frac{(.010)^2}{(.022)^2} = 30.99+ \text{ ohms.}$$

For a wire 400 feet long, we have, therefore, by direct proportion,

$$\text{Required resistance} = \frac{400}{1{,}800} \times 30.99 = 6.88+.$$

Ans. 6.88+ ohms.

If a circuit is made up of several different materials joined in series with each other, the resistance of the circuit is equal to the sum of the resistances of its several parts. In calculating the resistance of such a circuit, the resistance of each part should first be calculated, and the sum of these resistances will be the total resistance of the circuit.

The table on page 9 gives the resistance of chemically pure substances at 0° Centigrade or 32° Fahrenheit in International ohms. The first column of numbers gives the relative resistances when that of annealed silver is taken as unity. For example, mercury has 62.73 times the resistance of annealed silver. The second and third columns give the resistances of a foot of wire .001 inch in diameter, and of a meter of wire 1 millimeter in diameter, respectively. The fourth and fifth columns give respectively the resistance in microhms of a cubic inch and cubic centimeter, that is, the specific resistances.

Table Showing Relative Resistance of Chemically Pure Substances at Thirty-two Degrees Fahrenheit in International Ohms.

Metal.	Relative Resistance.	Resistance of a wire 1 foot long, .001 inch in diameter.	Resistance of a wire 1 meter long, 1 millimeter in diameter.	Resistance in Microhms.	
				Cubic Inch.	Cubic Centimeter.
Silver, annealed.	1.000	9.023	.01911	.5904	1.500
Copper, annealed.	1.063	9.585	.02028	.6274	1.594
Silver, hard drawn.	1.086	9.802	.02074	.6415	1.629
Copper, hard drawn.	1.086	9.803	.02075	.6415	1.629
Gold, annealed.	1.369	12.35	.02613	.8079	2.052
Gold, hard drawn.	1.393	12.56	.02661	.8224	2.088
Aluminum, annealed	1.935	17.48	.03700	1.144	2.904
Zinc, pressed.	3.741	33.76	.07143	2.209	5.610
Platinum, annealed.	6.022	54.34	.1150	3.555	9.032
Iron, annealed.	6.460	58.29	.1234	3.814	9.689
Lead, pressed.	13.05	117.7	.2491	7.706	19.58
German silver.	13.92	125.5	.2659	8.217	20.87
Platinum-silver alloy ($\frac{1}{3}$ platinum, $\frac{2}{3}$ silver.)	16.21	146.3	.3097	9.576	24.32
Mercury.	62.73	570.7	1.208	37.05	94.06

It should be noted that the resistances in the above table are for chemically pure substances, and also at 32° Fahrenheit. A very small portion of foreign matter mixed with a metal greatly increases its resistance. An alloy of two or more metals always has a higher specific resistance than that of any of its constituents. For example, the conductivity of silver mixed with 1.2 per cent in volume of gold, will be 59 when that of pure silver is taken as 100. Annealing reduces the resistance of metals.

The following examples are given to illustrate the use of the table above in connection with the formula at the top of page 8, and to show the application of preceding laws.

Example. — From the specific resistance of annealed aluminum as given in the next to the last column of the table, calculate the resistance given in the second column of figures for that substance.

Solution. — The resistance in microhms of a cubic inch of annealed aluminum at 32° F. is 1.144, which is equal to .000001144 ohms. The resistance of a wire 1 foot long and .001

inch in diameter is required. In the formula on page 8, we have $s = .000001144$, $L = 1$ foot $= 12$ inches and

$$A = \frac{\pi d^2}{4} = \frac{3.1416 \times .001^2}{4} = .0000007854 \text{ sq. in.}$$

Substituting these values in the formula,

$$R = s\frac{L}{A}$$

we have,

$$R = .000001144 \times \frac{12}{.0000007854}$$

$$= 17.48 \text{ ohms.} \qquad \text{Ans. } 17.48 \text{ ohms.}$$

Example.—The resistance in microhms of a cubic centimeter of annealed platinum at 32° F. is 9.032. What is the resistance of a wire of the same substance one meter long and one millimeter in diameter at the same temperature?

Solution. — In the formula for resistance we have the quantities $s = 9.032$ microhms $= .000009032$ ohms; $L = 1$ meter $=$ 100 centimeters; and

$$A = \frac{\pi d^2}{4} = \frac{3.1416 \times .1^2}{4} = .007854 \text{ sq. cm.}$$

the diameter being equal to 1 millimeter $= .1$ cm.

Substituting these values we have,

$$R = .000009032 \times \frac{100}{.007854}$$

$$= .1150 \text{ ohms.} \qquad \text{Ans. } .115 \text{ ohms.}$$

Example. — From the table the resistance of 1 ft. of pure annealed silver wire .001 inch in diameter at 32° F. is 9.023 ohms. What is the resistance of a mile of wire of the same substance .1 inch in diameter at that temperature?

Solution. — As the resistance of wires is directly proportional to their length and inversely proportional to the squares of their diameters, the required resistance is found by multiplying the resistance per foot by 5,280 and the product by the inverse squares of the diameters.

$$\text{Therefore } R = 9.023 \times 5280 \times \left\{\frac{.001}{.1}\right\}^2$$

$$= 4.76 \text{ ohms (approx.)}$$

Ans. 4.76 ohms.

Example.—A mile and one-half of an annealed wire of pure iron has a resistance of 46.1 ohms. What would be the resistance of hard drawn wire of pure copper of the same length and diameter, assuming each to be at the temperature of melting ice?

Solution. — The only factor involved by this example is the relative resistance of the two metals. From the table, page 9, annealed iron has 6.460 and hard-drawn copper 1.086 times the resistance of annealed silver. Hence the resistance of the copper is to that of the iron as 1.086 is to 6.460, and the required resistance is

$$R = 46.1 \times \frac{1.086}{6.460} = 7.75 \text{ ohms (approx.)}$$

Ans. 7.75 ohms.

Example. — If the resistance of a wire 7,423 feet long is 18.7 ohms, what would be its resistance if its length were reduced to 6,253 feet and its cross-section made one half again as large?

Solution. — As resistance is directly proportional to the length, and inversely proportional to the area of the cross-section, the required resistance is

$$R = 18.7 \times \frac{6253}{7423} \times \frac{2}{3} = 10.5 \text{ ohms (approx.)}$$

Ans. 10.5 ohms.

Resistance Affected by Heating. The resistance of metals depends upon the temperature, and the resistance is increased by heating. The heating of some substances, among which is carbon, causes a decrease in their resistance. The resistance of the filament of an incandescent lamp when lighted is only about half as great as when cold. All *metals*, however, have their resistance increased by a rise in temperature. The percentage increase in resistance with rise of temperature varies with the different metals, and varies slightly for the same metal at different temperatures. The increase is practically uniform for most metals throughout a considerable range of temperature. The resistance of copper increases about .4 per cent. per degree Centigrade, or about .22 per cent. per degree Fahrenheit. The percentage increase in resistance for alloys is much less than for the simple metals. Standard resistance coils are therefore made of alloys, as it is desirable that their resistance should be as nearly constant as possible.

The change in resistance of one ohm per degree rise in temperature for a substance is called the *temperature coefficient* for that substance. The following table gives the temperature coefficients for a few substances.

TEMPERATURE COEFFICIENTS.

MATERIAL.	RISE IN R. OF 1 OHM WHEN HEATED: 1° F.	1° C.
Platinoid	.00012	.00022
Platinum-silver	.00014	.00025
German silver	.00022	.00040
Platinum	.0019	.0035
Silver	.0021	.0038
Copper, aluminum	.0022	.0040
Iron	.0026	.0046

If the resistance of a conductor at a certain temperature is known, the resistance the conductor will have at a higher temperature may be found by multiplying the temperature coefficient for the substance, by the number of degrees increase and by the resistance at the lower temperature, and adding to this result the resistance at the lower temperature. The product of the temperature coefficient by the number of degrees increase gives the increase in resistance of one ohm through that number of degrees, and multiplying this by the number of ohms gives the increase in resistance for the conductor. The result obtained is practically correct for moderate ranges of temperature.

The above method of calculating the resistance of conductors at increased temperatures is conveniently expressed by the following formula:

$$R_2 = R_1 (1 + a\,t)$$

where R_2 is the resistance at the higher temperature, R_1 that at the lower temperature, a the temperature coefficient for the substance and t the number of degrees change.

From the preceeding formula it follows that if the resistance at the higher temperature is known, that at the lower temperature will be given by the formula:

$$R_1 = \frac{R_2}{1 + at}$$

In calculating resistances at different temperatures, the temperature coefficient based on the Fahrenheit scale should be used if the number of degrees change is given in degrees Fahrenheit, and that based on the Centigrade scale if given in degrees Centigrade.

Example.— The resistance of a coil of German silver wire at 12° C. is 1304 ohms. What would be its resistance at a temperature of 60° C.?

Solution.— From the statement of the example $R_1 = 1304$, $t = 60 - 12 = 48$, and from the table page 12, $a = .0004$. Substituting these values in the first of the preceding formulas we have,

$$\begin{aligned} R_2 &= 1304\ (1 + .0004 \times 48) \\ &= 1304 \times 1.0192 \\ &= 1329 \text{ ohms (approx.)} \end{aligned}$$

Ans. 1329 ohms.

Example. — If the resistance of a copper conductor at 95° F. is 48.2 ohms, what would be the resistance of the same conductor at 40° F.?

Solution. — In this case $R_2 = 48.2$, $t = 95 - 40 = 55$, and from the table $a = .0022$. Substituting these values in the formula at the foot of page 12, we have,

$$\begin{aligned} R_1 &= \frac{48.2}{1 + .0022 \times 55} = \frac{48.2}{1.121} \\ &= 43. \text{ ohms (approx.)} \end{aligned}$$

Ans. 43 ohms.

The first table on page 14 gives the resistance of the most common sizes of copper wire according to the American or Brown and Sharpe (B. & S.) gauge. The resistance given is for pure copper wire at a temperature of 75° F. or 24° C.

The first column gives the number of the wire, the second the diameter in thousandths of an inch or mils, and the third the diameter in millimeters, The fourth column gives the equivalent number of wires each one mil or one thousandth of an inch in diameter. This is called the size of the wire in circular mils and is equal to the square of the diameter in mils. The fifth column gives the ohms per thousand feet and the resistance per mile is found by multiplying these values by 5.28. Ordinary commercial

copper has a conductivity of about 95 to 97 per cent. of that of pure copper. The resistance of commercial wire is therefore about 3 to 5 per cent. greater than the values given in the table. The resistance for any metal other than copper may be found by multiplying the resistance given in the table by the ratio of the specific resistance of the given metal to the specific resistance of copper.

American Wire Gauge (B. & S.)

No.	Diameter in		Circular Mils.	Ohms per 1000 Ft.	No.	Diameter in		Circular Mils.	Ohms per 1000 Ft.
	Mils.	Millim.				Mils.	Millim.		
0000	460.00	11.684	211600.0	.051	19	35.89	.912	1288.0	8.617
000	409.64	10.405	167805.0	.064	20	31.96	.812	1021.5	10.566
00	364.80	9.266	133079.4	.081	21	28.46	.723	810.1	13.323
0	324.95	8.254	105592.5	.102	22	25.35	.644	642.7	16.799
1	289.30	7.348	83694.2	.129	23	22.57	.573	509.5	21.185
2	257.63	6.544	66373.0	.163	24	20.10	.511	404.0	26.713
3	229.42	5.827	52634.0	.205	25	17.90	.455	320.4	33.684
4	204.31	5.189	41742.0	.259	26	15.94	.405	254.0	42.477
5	181.94	4.621	33102.0	.326	27	14.19	.361	201.5	53.563
6	162.02	4.115	26250.5	.411	28	12.64	.321	159.8	67.542
7	144.28	3.665	20816.0	.519	29	11.26	.286	126.7	85.170
8	128.49	3.264	16509.0	.654	30	10.03	.255	100.5	107.391
9	114.43	2.907	13094.0	.824	31	8.93	.227	79.7	135.402
10	101.89	2.588	10381.0	1.040	32	7.95	.202	63.2	170.765
11	90.74	2.305	8234.0	1.311	33	7.08	.180	50.1	215.312
12	80.81	2.053	6529.9	1.653	34	6.30	.160	39.7	271.563
13	71.96	1.828	5178.4	2.084	35	5.61	.143	31.5	342.443
14	64.08	1.628	4106.8	2.628	36	5.00	.127	25.0	431.712
15	57.07	1.450	3256.7	3.314	37	4.45	.113	19.8	544.297
16	50.82	1.291	2582.9	4.179	38	3.96	.101	15.7	686.511
17	45.26	1.150	2048.2	5.269	39	3.53	.090	12.5	865.046
18	40.30	1.024	1624.1	6.645	40	3.14	.080	9.9	1091.865

The following table gives the size of the English or Birmingham wire gauge. The B. & S. is however much more frequently used in this country. The Brown and Sharpe gauge is a little smaller than the Birmingham for corresponding numbers.

Stubs' or Birmingham Wire Gauge (B. W. G.)

No.	Diameter in		No.	Diameter in		No.	Diameter in	
	Mils.	Millim.		Mils.	Millim.		Mils.	Millim.
0000	454	11.53	8	165	4.19	18	49	1.24
00	380	9.65	10	134	3.40	20	35	0.89
1	300	7.62	12	109	2.77	24	22	0.55
4	238	6.04	14	83	2.11	30	12	0.31
6	203	5.16	16	65	1.65	36	4	0.10

Example.— A telegraph line 100 miles long consists of No. 6 B. & S. iron wire. Compare its resistance at 75° F. with that of a similar line of No. 14 copper wire. What will their resistances be at 50° F.?

Solution.— The resistance of 100 miles of No. 14 copper is

$$100 \times 5.28 \times 2.628 = 1{,}402 \text{ ohms (nearly).}$$

The resistance of 100 miles of No. 6 iron wire is

$$100 \times 5.28 \times .411 \times 6.46 = 1{,}388 \text{ ohms (approximately).}$$

At 50° F. the copper wire has a resistance of

$$\frac{1{,}402}{1 + .0022 \times 25} = \frac{1{,}402}{1.055} = 1{,}329 \text{ ohms (nearly).}$$

The resistance of the iron wire is

$$\frac{1{,}388}{1 + .0026 \times 25} = \frac{1{,}388}{1.065} = 1{,}303 \text{ ohms (nearly).}$$

Ans. 1,303 ohms and 1,329 ohms.

On pages 16 and 17 is given a table disclosing among other data the resistance of various primary cells. The resistance of a circuit of which a battery forms a part, is made up of the external resistance, or the resistance of outside wires and connections, and the internal resistance, or the resistance of the battery itself. The table referred to gives in the first column the name of the cell. In the second and third column appears the name of the anode and kathode respectively. These terms are commonly used with reference to electrolysis but may also be applied to primary cells. The current passes from the anode to the kathode through the cell, and therefore with reference to the cell itself, the anode may be considered the positive element and the kathode the negative element. In regard to the outside circuit however, the current passes of course, from the kathode to the anode, and hence with reference to the outside circuit the kathode is positive and the anode negative; ordinarily the external circuit is considered. As the anode of almost all primary cells is zinc it may readily be remembered that the current passes from the other element *to* the zinc through the *external* circuit. The fourth and fifth columns of the table give the excitant and depolarizer respectively. The sixth column gives the E. M. F. of each cell when it is supplying no current, and the last column gives the internal resistance in ohms.

TABLE IN RELATION TO PRIMARY CELLS, ELECTROMOTIVE FORCE, RESISTANCE, ETC.

NAME OF CELL.	ANODE.	KATHODE.	EXCITANT.	DEPOLARIZER.	E. M. F. IN VOLTS.	INTERNAL RESISTANCE IN OHMS.
Volta (Wollaston, etc.)	Zinc	Copper	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	
Smee	Zinc	Platinized Silver	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	0.5
Law	Zinc	Carbon	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	
Poggendorff (Grenet)	Zinc	Graphite (Carbon)	Solution of Sulphuric Acid (H_2SO_4)	Potassium Dichromate ($K_2Cr_2O_7$)	2.1	
Poggendorff (Grenet) two fluid	Zinc	Graphite (Carbon)	Saturated Solution of Potassium Dichromate and Sulphuric Acid	None Separate	1.96	.001 to .08
Grove	Zinc	Platinum	Sulphuric Acid dilute (H_2SO_4)	Nitric Acid (HNO_3)	1.96	0.1 to 0.12
Bunsen	Zinc	Graphite (Carbon)	Sulphuric Acid dilute (H_2SO_4)	Nitric Acid	1.8 to 1.96	0.08 to 0.11
				Chromic Acid	1.8	0.1 to 0.12
Leclanche	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl)	Manganese Dioxide (MnO_2)	1.4 to 1.6	1.13 to 1.15
Lalande Lalande—Chaperon	Zinc	Graphite (Carbon)	Caustic Potash or Potassium Hydrate (KOH)	Cupric Oxide	0.8 to 0.98	1.3
Upward	Zinc	Graphite (Carbon)	Zinc Chloride ($ZnCl_2$)	Chlorine (Cl)	2.0	
Fitch	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl)	Sodium & Potassium Chlorates ($NaClO_3 + KClO_3$)	1.1	
Papst	Iron	Graphite (Carbon)	Ferric Chloride (Fe_2Cl_6)	(Fe_2Cl_6)	0.4	
Obach (dry)	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl) in Calcium Sulphate ($CaSO_4$)	Manganese Dioxide (MnO_2)	1.46	
Daniell (Meidinger Minotto, etc.)	Zinc	Copper	Zinc Sulphate ($ZnSO_4$)	Copper Sulphate ($CuSO_4$)	1.079	2 to 5
De la Rue	Zinc	Silver	Ammonium Chloride	Silver Chloride ($AgCl$)	1.03 to 1.42	0.4 to 0.6
Marie Davy	Zinc	Graphite (Carbon)	Sulphuric Acid dilute (H_2SO_4)	Paste of Sulphate of Mercury (Hg_2SO_4)	1.52	0.75 to 1
Clark (Standard)	Zinc	Mercury	Zinc Sulphate ($ZnSo_4$)	Mercurous Sulphate (Hg_2SO_4)	1.434*	0.3 to 0.5
Weston	Cadmium	Mercury	Cadmium Sulphate ($CdSO_4$)	Mercurous Sulphate (Hg_2SO_4)	1.025	

NAME OF CELL.	ANODE.	KATHODE.	EXCITANT.	DEPOLARIZER.	E. M. F. IN VOLTS.	INTERNAL RESISTANCE IN OHMS.
Von Helmholtz	Zinc	Mercury	Zinc Chloride ($Zn\,Cl_2$)	Mercurous Chloride ($Hg_2\,Cl_2$)	1.0	
Chromic Acid single fluid	Zinc	Graphite (Carbon)	Sulphuric and Chromic Acids, dilute mixed	None Separate	2.2	.016 to .08
Fuller	Zinc	Graphite (Carbon)	Sulphuric Acid (H_2SO_4)	Potassium Dichromate ($K_2\,Cr_2\,O_7$)	2.0	0.5 to 0.7
Gaiffe	Zinc	Silver	Zinc Chloride ($Zn\,Cl_2$)	Silver Chloride (Ag Cl)	1.02	0.5 to 0.6
Maiche	Zinc scraps in bath of Mercury	Platinized Carbon	Common Salt Solution *i. e.* Sodium Chloride (NaCl)	None Separate	1.35	1 to 2
Niaudet	Zinc	Graphite (Carbon)	Common Salt Solution *i. e.* Sodium Chloride (NaCl)	Chloride of Calcium (Lime) ($Ca\,Cl_2$)	1.0 to 1.6	5 to 6
Schanschieff	Zinc	Graphite (Carbon)	Mercurial Solution	None Separate	1.56	0.05 to 0.75
Skrivanoff	Zinc	Silver	Caustic Potash or Potassium Hydrate (KOH)	Chloride of Silver (Ag Cl)	1.5	1.5

* At 15 degrees Centigrade or 59 degrees Fahrenheit.

Resistances in last column measured in cells standing 6″ × 4″

OHM'S LAW.

One of the most important and most used laws of electricity is that first formulated by Dr. G. S. Ohm, and known as Ohm's law. This law is as follows:

The current is directly proportional to the electromotive force and inversely proportional to the resistance.

That is, if the electromotive force applied to a circuit is increased, the current will be increased in the same proportion, and if the resistance of a circuit is increased then the current will be decreased proportionally. Likewise a decrease in the electromotive force causes a proportional decrease in current and a decrease in resistance causes a proportional increase in current. The current depends only upon the electromotive force and resistance and in the manner expressed by the above simple law. The law may be expressed algebraically as follows:

$$\text{current } \textit{varies as } \frac{\text{electromotive force}}{\text{resistance}}$$

The units of these quantities, the ampere, volt and ohm, have been so chosen that an electromotive force of 1 volt applied to a resistance of 1 ohm, causes 1 ampere of current to flow. Ohm's law may therefore be expressed by the following equation:

$$I = \frac{E}{R}$$

where I is the current in amperes, E the electromotive force in volts and R the resistance in ohms.

It is therefore evident, that if the electromotive force and resistance are known the current may be found, or if any two of the three quantities are known the third may be found. If the current and resistance are known the electromotive force may be found from the formula:

$$E = RI$$

and if the current and electromotive force are known, the resistance may be found from the formula:

$$R = \frac{E}{I}$$

Simple Applications. The following examples are given to illustrate the simplest applications of Ohm's law.

Example. — If the E.M.F. applied to a circuit is 4 volts and its resistance is 2 ohms, what current will flow?

Solution. — By the formula for current,

$$I = \frac{E}{R} = \frac{4}{2} = 2 \text{ amperes.}$$

Ans. 2 amperes.

Example. — What voltage is necessary to cause a current of 23 amperes to flow through a resistance of 820 ohms?

Solution. — By the formula for E.M.F.,

$$E = RI = 820 \times 23 = 18{,}860 \text{ volts.}$$

Ans. 18,860 volts.

Example. — The E.M.F. applied to a circuit is 110 volts, and it is desired to obtain a current of .6 ampere. What should be the resistance of the circuit?

Solution. — By the formula for resistance,

$$R = \frac{E}{I} = \frac{110}{.6} = 183.+ \text{ ohms.}$$

Ans. 183. ohms.

Series Circuits. A circuit made up of several parts all joined in series with each other, is called a series circuit and the resistance of the entire circuit is of course the sum of the separate resistances. In calculating the current in such a circuit the total resistance must first be obtained, and the current may then be found by dividing the applied or total E.M.F. by the total resistance. This is expressed by the formula,

$$I = \frac{E}{R_1 + R_2 + R_3 + \text{etc.}}$$

Example. — Three resistance coils are connected in series with each other and have a resistance of 8, 4 and 17 ohms respectively. What current will flow if the E.M.F. of the circuit is 54 volts?

Solution. — By the preceding formula,

$$I = \frac{E}{R_1 + R_2 + R_3} = \frac{54}{8 + 4 + 17} = \frac{54}{29} = 1.8+ \text{amperes.}$$

Ans. 1.8+ amperes.

Example. — Six arc lamps, each having a resistance of 5 ohms, are connected in series with each other and the resistance of the connecting wires and other apparatus is 3.7 ohms. What must be the pressure of the circuit to give a desired current of 9.6 amperes?

Solution. — The total resistance of the circuit is $R = (6 \times 5) + 3.7 = 33.7$ ohms and the current is to be $I = 9.6$ amperes. Hence by the formula for E.M.F.,

$$E = R\,I = 33.7 \times 9.6 = 323.+ \text{ volts.}$$

Ans. 323.+ volts.

Example. — The current passing in a certain circuit was 12 amperes and the E.M.F. was 743 volts. The circuit was made up of 4 sections all connected in series, and the resistance of three sections was 16, 9 and 26 ohms respectively. What was the resistance of the fourth section?

Solution. — Let x = the resistance of the fourth section, then $R = 16 + 9 + 26 + x = 51 + x$, $I = 12$, and $E = 743$. By the formula for resistance,

$$R = \frac{E}{I} \text{ or, } \quad 51 + x = \frac{743}{12} = 61.9 \text{ ohms (approx.)}$$

If $51 + x = 61.9$ we have, by transposing 51 to the other side of the equation,

$$x = 61.9 - 51 = 10.9 \text{ ohms.}$$

Ans. 10.9 ohms.

Example. — A current of 54 amperes flowed through a circuit when the E.M.F. was 220 volts. What resistance should be added in series with the circuit to reduce the current to 19 amperes?

Solution. — The resistance in the first case was,

$$R = \frac{220}{54} = 4.07 \text{ ohms (approx.)}$$

The resistance in the second must be,

$$R = \frac{220}{19} = 11.58 \text{ ohms (approx.)}$$

The required resistance to insert in the circuit is the difference of these two resistances, or $11.58 - 4.07 = 7.51$ ohms.

Ans. 7.51 ohms.

Fall of Potential in a Circuit. Fig. 1 illustrates a series circuit in which the resistances A, B, C, D and E are connected in series with each other and with the source of electricity. If the E. M. F. is known, the current may be found by dividing the E. M. F. by the sum of all the resistances. Ohm's law may, however, be applied to any part of a circuit separately, as well as to the complete circuit. Suppose the resistances of A, B, C, D and E are 4, 3, 6, 3 and 4 ohms respectively, and assume that the source has no resistance. Suppose the current flowing to be 12 amperes. The E. M. F. necessary to force a current of 12 amperes through the resistance A of 4 ohms is, by applying Ohm's law, equal to $E = RI = 4 \times 12 = 48$ volts. Hence between the points a and b outside of the resistance A, there must be a difference of potential of 48 volts to force the current through this resistance. Also to force the same current through B, the voltage necessary is $3 \times 12 = 36$. Similarly, for each part C, D and E, there are required 72, 36 and 48 volts respectively.

As 48 volts are necessary for part A and 36 volts for part B, it is evident that to force the current through both parts a difference of potential of $48 + 36 = 84$ volts is required; that is, the

voltage between the points *a* and *c* must be 84 volts. For the three parts *A*, *B* and *C*, 48 + 36 + 72 = 156 volts are necessary, and for the entire circuit, 240 volts must be applied to give the current of 12 amperes. From the above it is evident that there is a gradual fall of potential throughout the circuit, and if the voltage between any two points of the circuit be measured, the E. M. F. obtained would depend upon the resistance included between these two points. For example, the voltage between points *b* and *d* would be found to be 72 + 36 = 108 volts, or between *d* and *e* 36, volts, etc. From the preceding it is apparent that the fall of potential in a part of a circuit is equal to the current multiplied by the resistance of that part.

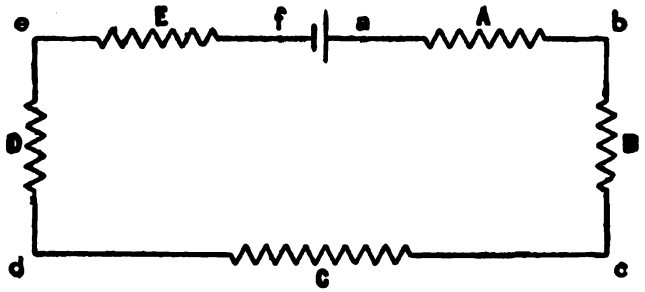


Fig. 1.

This gradual fall of potential, or *drop* as it is commonly called, throughout a circuit, enters into the calculations for the size of conductors or mains supplying current to distant points. The resistances of the conductors cause a certain drop in transmitting the current, depending upon their size and length, and it is therefore necessary that the voltage of machines at the supply station shall be great enough to give the voltage necessary at the receiving stations as well as the additional voltage lost in the conducting mains.

For example, in Fig. 1 the voltage necessary between the points *e* and *b* is 144 volts, but to give this voltage the source must supply in addition the voltage lost in parts *A* and *E*, which equals 96 volts.

Example.—The voltage required by 17 arc lamps connected in series is 782 volts and the current is 6.6 amperes. The resist-

ance of the connecting wires is 7 ohms. What must be the E. M. F. applied to the circuit?

Solution.—The drop in the connecting wires is $E = RI = 7 \times 6.6 = 46.2$ volts. The E. M. F. necessary is therefore $782 + 46.2 = 828.2$ volts. Ans. 828.2 volts.

Example.—The source of E. M. F. supplies 114 volts to a circuit made up of incandescent lamps and conducting wires. The lamps require a voltage of 110 at their terminals, and take a current of 12 amperes. What should be the resistance of the conducting wires in order that the lamps will receive the necessary voltage?

Solution.—The allowable drop in the conducting wires is $114 - 110 = 4$ volts. The current to pass through the wires is 12 amperes. Hence the resistance must be

$$R = \frac{E}{I} = \frac{4}{12} = .33 + \text{ohms.}$$

Ans. .33 + ohms.

Divided Circuits. When a circuit divides into two or more parts, it is called a *divided* circuit and each part will transmit a portion of the current.

Such a circuit is illustrated in Fig. 2, the two branches being represented by *b* and *c*. The current passes from the positive pole of the battery through *a* and then divides; part of the current passing through *b* and part through *c*. The current then unites and passes through *d* to the negative pole of the battery. The part *c* may be considered as the main part of the circuit and *b* as a by-pass about it. A branch which serves as a by-pass to another circuit is called a *shunt* circuit, and the two branches are said to be connected in *parallel*.

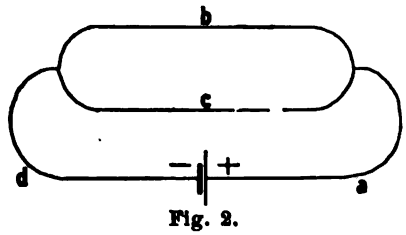


Fig. 2.

In considering the passage of a current through a circuit of this sort, it may be necessary to determine how much current will pass through one branch and how much through the other. Evidently this will depend upon the relative resistance of the two branches, and more current will pass through the branch offering the lesser resistance than through the branch having the higher

resistance. If the two parts have equal resistances, then one half of the total current will pass through each branch. If one branch has twice the resistance of the other, then only one-half as much of the total current will pass through that branch as through the other; that is, $\frac{1}{3}$ of the total current will pass through the first branch and the remaining $\frac{2}{3}$ will pass through the second.

The relative strength of current in the two branches will be inversely proportional to their resistances, or directly proportional to their conductances.

Suppose the resistance of one branch of a divided circuit is r_1 (see Fig. 3), and that of the other is r_2. Then by the preceding law,

$$\text{current in } r_1 : \text{current in } r_2 :: r_2 : r_1$$

Also,

$$\text{current in } r_1 : \text{total current} :: r_2 : r_1 + r_2$$

and

$$\text{current in } r_2 : \text{total current} :: r_1 : r_1 + r_2$$

Let I represent the total current, i_1 the current through the resistance r_1 and i_2 the current through the resistance r_2. Then the two preceding proportions are expressed by the following formulas:

$$i_1 = \frac{Ir_2}{r_1 + r_2} \quad \text{and} \quad i_2 = \frac{Ir_1}{r_1 + r_2}$$

Example.—The total current passing in a circuit is 24 amperes. The circuit divides into two branches having resistances of 5 and 7 ohms respectively. What is the current in each branch?

Solution.—In this case $I = 24$, $r_1 = 5$ and $r_2 = 7$. Substituting these values in the above formulas we have,

$$i_1 = \frac{Ir_2}{r_1 + r_2} = \frac{24 \times 7}{5 + 7} = 14 \text{ amperes.}$$

and

$$i_2 = \frac{Ir_1}{r_1 + r_2} = \frac{24 \times 5}{5 + 7} = 10 \text{ amperes.}$$

Ans. { In 5 ohm branch, 14 amperes.
In 7 ohm branch, 10 amperes.

Joint Resistance of Divided Circuits. As a divided circuit

offers two paths to the current, it follows that the joint resistance of the two branches will be less than the resistance of either branch alone. The ability of a circuit to conduct electricity is represented by its conductance, which is the reciprocal of resistance; and the conductance of a divided circuit is equal to the sum of the conductances of its parts.

For example, in Fig. 3, the conductance of the upper branch equals $\frac{1}{r_1}$ and that of the lower branch equals $\frac{1}{r_2}$. If R represents the joint resistance of the two parts then the joint conductance equals:

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} = \frac{r_1 + r_2}{r_1 r_2}$$

Having thus obtained the joint conductance, the joint resistance is found by taking the reciprocal of the conductance, that is,

$$R = \frac{r_1 r_2}{r_1 + r_2}$$

This formula may be stated as follows:

The joint resistance of a divided circuit is equal to the product of the two separate resistances divided by their sum.

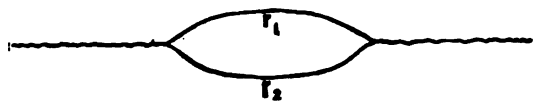


Fig. 3.

For example, suppose the resistance of each branch to be 2 ohms. The conductance of the circuit will be,

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{2} = 1, \text{ and hence } R = 1 \text{ ohm.}$$

Also by the preceding formula,

$$R = \frac{2 \times 2}{2 + 2} = 1 \text{ ohm.}$$

The resistance of a divided circuit in which each branch has a resistance of 2 ohms is therefore 1 ohm.

Example.—The resistances of two separate conductors are 8

and 7 ohms respectively. What would be their joint resistance if connected in parallel?

Solution.—In this case $r_1 = 3$ and $r_2 = 7$, hence by the formula,

$$R = \frac{3 \times 7}{3 + 7} = 2.1 \text{ ohms.} \qquad \text{Ans. 2.1 ohms.}$$

Suppose, as illustrated in Fig. 4, the conductors having resistances equal to r_1, r_2 and r_3 respectively, are connected in

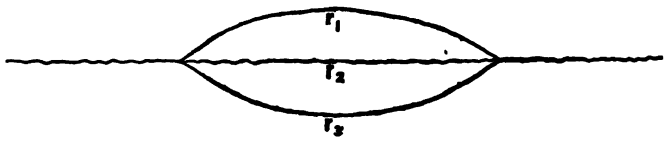


Fig. 4.

parallel. The joint total conductance will then be equal to,

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} = \frac{r_2 r_3 + r_1 r_3 + r_1 r_2}{r_1 r_2 r_3}$$

and as the joint resistance is the reciprocal of the joint conductance, the joint resistance R of the three branches is expressed by the formula,

$$R = \frac{r_1 r_2 r_3}{r_2 r_3 + r_1 r_3 + r_1 r_2}$$

Example.—What is the joint resistance when connected in parallel, of three wires whose respective resistances are 41, 52 and 29 ohms respectively?

Solution.—In this case $r_1 = 41$, $r_2 = 52$ and $r_3 = 29$. Hence, by the preceding formula,

$$R = \frac{41 \times 52 \times 29}{52 \times 29 + 41 \times 29 + 41 \times 52} = 12.8 + \text{ohms.}$$

Ans. 12.8 + ohms.

In general, for any number of conductors connected in parallel, the joint resistance is found by taking the reciprocal of the sum of the reciprocals of the separate resistances.

Example.—A circuit is made up of five wires connected in parallel, and their separate resistances are respectively 12, 21, 28, 8 and 42 ohms. What is the joint resistance?

Solution.—The sum of the conductances is:

$$\frac{1}{12}+\frac{1}{21}+\frac{1}{28}+\frac{1}{8}+\frac{1}{42}=\frac{53}{168}$$

Hence the joint resistance equals:

$$R=\frac{168}{53}=3.1+\text{ ohms.}$$ Ans. 3.1 + ohms.

If the resistance of each branch is known and also the potential difference between the points of union, then the current in each branch may be found by applying Ohm's law to each branch separately. For example, if this potential difference were 96 volts, and the separate resistances of the 4 branches were 8, 24, 3 and 48 ohms respectively, then the current in the respective branches would be 12, 4, 32 and 2 amperes respectively.

By combining the preceding principles, many problems may be solved involving current, resistance and potential.

Example.— A 40-ohm wire and a 50-ohm wire are connected in parallel. In series with the pair is a group of three wires in parallel, of 12, 15 and 20 ohms respectively. If a total current of 4 amperes is required and the resistance of the connecting wires is .4 ohm, what total electromotive force will be required? What difference of potential will exist between the ends of the group of three wires?

Solution.— The joint resistance of the pair of wires is

$$\frac{40\times 50}{40+50}=\frac{2{,}000}{90}=22.2\text{ ohms.}$$

The resistance of the group of three wires is

$$\frac{12\times 15\times 20}{15\times 20+12\times 20+12\times 15}=\frac{3{,}600}{720}=5\text{ ohms.}$$

Hence the total resistance of the circuit is

$$22.2+5+.4=27.6\text{ ohms.}$$

The electromotive force required at the terminals is

$$E=RI=27.6\times 4=110.4\text{ volts.}$$

To find the difference of potential between the ends of any part of the circuit when the current is flowing, as in the case of the group of three wires, we have, from the formula,

$$E=RI=5\times 4=20.$$

Ans. 110.4 volts and 20 volts.

Battery Circuits. Fig. 5 illustrates a simple circuit having a single cell C connected in series with a resistance. This is the customary manner of representing a cell, the short, heavy line representing the zinc and the long light line representing the copper or carbon plate. In determining the amount of current which will flow in such a circuit, the total resistance of the circuit must be considered. This is made up of the external resistance R and the internal resistance r, or the resistance of the cell itself. If E represents the total E. M. F. of the cell, then the current I which will flow is expressed by the formula,

$$I = \frac{E}{R + r}$$

It has been shown that whenever a current passes through any resistance, there is always a certain *drop* or fall of potential. The total E. M. F. above referred to, expresses the total potential difference between the plates of the cell and is the E. M. F. of the cell on *open* circuit. When the current flows, however, there is a fall of potential or loss of voltage within the cell itself, and hence the E. M. F. of the cell on closed circuit is less than on open circuit. That is, if the voltage be measured when the cell is supplying current, it will be found to be less than when the voltage is measured on open circuit, or when the cell is supplying no current. The voltage on closed circuit is that available for the external circuit, and is therefore called the *external* or *available* voltage or E. M. F.

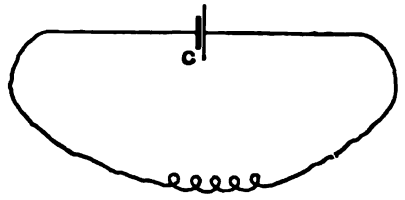


Fig. 5.

The external E. M. F. depends of course upon the strength of current the cell is supplying, and may be calculated as follows:

If the current passing is I and the resistance of the cell is r, then from Ohm's law the voltage lost in the cell equals rI. If E represents the total E. M. F. of the cell and E_1 the external E. M. F., then,

$$E_1 = E - rI$$

The E. M. F. of a cell is understood to be the total E. M. F. unless otherwise stated.

When two or more cells are interconnected they are said to form a *battery*.

Fig. 6 illustrates three cells connected in series with each other and with the external circuit. That is, the positive terminal of one cell is connected to the negative of the next, and the positive of that cell to the negative of the adjacent, etc. By this method of connecting, the E. M. F. of each cell is added to that of the others, so that the total E. M. F. of the circuit is three times that of a single cell. If one of the cells were connected so that its E. M. F. opposed that of the other two, it would offset the E. M. F. of one of the cells and the resultant E. M. F. would be that of a single cell. The connecting of cells in series as in Fig. 6 not only increases the E. M. F. of the circuit but also increases the internal resistance, the resistance of each cell being added to that of the others. If E equals the E. M. F. of each cell, r the internal resistance of each and R the external resistance, then the current that will flow is expressed by the formula,

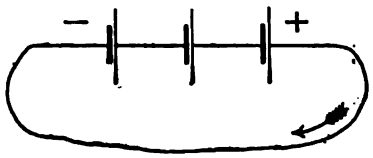


Fig. 6.

$$I = \frac{3E}{R + 3r}$$

or for n cells connected in series the formula for current is,

$$I = \frac{nE}{R + nr}$$

Fig. 7 illustrates two cells connected in parallel, and supplying current to an external circuit. Here the two positive terminals are connected with each other and also the two negative. The E. M. F. supplied to the circuit is equal to that of a single cell only. In fact connecting cells in parallel, is equivalent to enlarging the

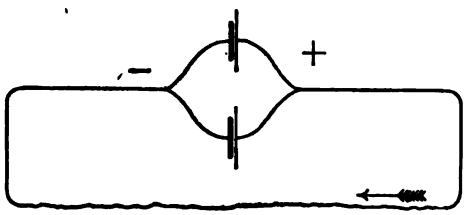


Fig. 7.

plates, and the only effect is to decrease the internal resistance. It is evident that coupling two cells in parallel affords two paths for the current and so decreases the resistance of the two cells to one-half that of a single cell. The formula expressing the current that would flow in the external circuit with two cells in parallel is therefore,

$$I = \frac{E}{R + \frac{r}{2}}$$

or for n cells connected in parallel, the formula for current is,

$$I = \frac{E}{R + \frac{r}{n}}$$

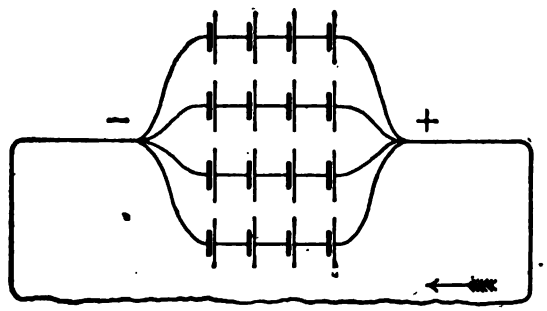


Fig. 8.

Fig. 8 represents a combination of the series and parallel method of connecting and represents four files of cells joined in parallel and each file having four cells connected in series. The E. M. F. of each file and consequently of the circuit is 4 E. The resistance of each file is 4 r and that of all the files $\frac{4r}{4}$. Hence, the formula for current is,

$$I = \frac{4E}{R + \frac{4r}{4}}$$

If there were n files connected in parallel and m cells were

connected in series in each file, the formula expressing the current in the external circuit would be,

$$I = \frac{m E}{R + \frac{m r}{n}}$$

where E is the E. M. F. of each cell, R the external resistance, and r the internal resistance of each cell.

The most advantageous method of connecting cells depends upon the results desired, the resistance of the cell and the external resistance. Suppose it is desired to pass a current through an external resistance of 2 ohms, and that Daniell's cells are to be used each having an E. M. F. of 1 volt and an internal resistance of 3 ohms.

With one cell only in circuit, the current will be,

$$\frac{E}{R + r} = \frac{1}{2 + 3} = .2 \text{ ampere,}$$

and with 5 cells all in series the current will be,

$$\frac{5 E}{R + 5 r} = \frac{5}{2 + 15} = .3 \text{ ampere (approx.).}$$

Therefore with 5 cells in series the current is only .1 ampere greater than with a single cell, and with 100 cells in series the current is only,

$$\frac{100 E}{R + 100 r} = \frac{100}{2 + 300} = .33 \text{ ampere.}$$

Hence with a comparatively low external resistance, there is but little gain in current strength by the addition of cells in series. This is due to the fact that, although the E. M. F. is increased 1 volt by each cell, the resistance is increased by 3 ohms.

Now suppose 5 Daniell cells to be connected in parallel with the external circuit of 2 ohms. The E. M. F. of the circuit will then be that of a single cell and the current will be,

$$\frac{E}{R + \frac{r}{5}} = \frac{1}{2 + \frac{3}{5}} = .4 \text{ ampere (nearly),}$$

and with 100 cells connected in parallel the current will be,

$$\frac{E}{R+\frac{r}{100}} = \frac{1}{2+\frac{3}{100}} = .5 \text{ ampere (nearly).}$$

A larger current is therefore obtained in this case by connecting the cells in parallel than by connecting them in series.

With a large external resistance on the other hand, a larger current is obtained by connecting the cells in series. For example, suppose the external resistance to be 500 ohms. One cell will then give a current of .00198 + ampere, and 5 cells in series will give about .0097 ampere, whereas 100 cells will give .125 ampere. With 5 cells connected in parallel the current will be .00199 + ampere, and with 100 cells the current will amount to approximately .002 ampere. With an external resistance of 500 ohms, there is practically no advantage in connecting the cells in parallel. The only effect of the latter method is to decrease the internal resistance which is almost negligible in comparison with the external resistance.

It may be shown mathematically that for a given external resistance and a given number of cells, the largest current is obtained when the internal resistance is *equal* to the external resistance. In order to obtain this result the values of m and n in the formula on page 30, should be so chosen that $\frac{m\,r}{n}$ equals R. This arrangement, although giving the largest current strength, is not the most economical. With the internal resistance equal to the external resistance there is just as much energy used up in the battery itself as is expended usefully in the external circuit.

In order to obtain the most economical arrangement, the internal resistance should be made as small as possible, that is, all the cells should be connected in parallel. The loss of power in the battery is then the smallest amount possible.

In order to obtain the quickest action of the current the cells should be connected in series. When the external circuit possesses considerable self-induction, as is the case when electromagnets are connected in the circuit, the action of the current is retarded.

This retardation may be decreased by having a high internal resistance, which is obtained by connecting the cells in series.

Example.—Sixteen cells, each having an internal resistance of .1 ohm are to be connected with a circuit whose resistance is .4 ohm. How should the cells be connected to obtain the greatest current?

Solution.—Here the external resistance R, equals .4 ohm and the resistance r of each cell equals .1 ohm. For maximum current,

$$\frac{m\,r}{n} = R, \text{ or } \frac{.1\,m}{n} = .4$$

Therefore, $$m = 4\,n$$

and as $m\,n = 16$, the only values of m and n which will be true for both of these equations are $m = 8$ and $n = 2$. Hence there must be 2 files of cells, with 8 cells in series in each file.

Ans. 2 files, 8 cells in each.

Example.—The external resistance in a circuit is 4 ohms. The cells used each have an E. M. F. of 1.2 volts and an internal resistance of 3.8 ohms. If 20 cells were used, which method of connecting would supply the larger current, — 5 files with 4 cells in series, or 4 files with 5 cells in series?

1st Solution.—Applying the formula on page 30, we have $R = 4$, $E = 1.2$, $r = 3.8$ and with 5 files and 4 in series, $m = 4$ and $n = 5$. Hence, the current is,

$$\frac{m\,E}{R + \frac{m\,r}{n}} = \frac{4 \times 1.2}{4 + \frac{4 \times 3.8}{5}} = .681 + \text{ampere.}$$

With 4 files and 5 cells in series, $m = 5$ and $n = 4$. Hence the current is,

$$\frac{5 \times 1.2}{4 + \frac{5 \times 3.8}{4}} = .685 + \text{ampere.}$$

The larger current is therefore supplied by having 4 files with 5 cells in series. Ans. 4 files, with 5 cells in series.

2nd Solution.—The maximum current is supplied when the

internal resistance equals the external resistance or when

$$\frac{m\,r}{n} = R.$$

With 5 files and 4 cells in series,

$$\frac{m\,r}{n} = \frac{4 \times 3.8}{5} = 3.04 \text{ ohms,}$$

and with 4 files and 5 cells in series,

$$\frac{m\,r}{n} = \frac{5 \times 3.8}{4} = 4.75 \text{ ohms.}$$

The latter value is nearer to 4 ohms, which is the external resistance, than is 3.04, hence the larger current will be supplied with 4 files and 5 cells in series. Ans. 4 files, with 5 cells in series.

Example.—It is desired to pass a current of .025 ampere through an external resistance of 921 ohms. The cells are to be connected in series and each has an E. M. F. of .8 volt and an internal resistance of 1.3 ohms. What number of cells must be used?

Solution.—From page 28, the general formula for cells in series is,

$$I = \frac{nE}{R + n\,r}$$

and in this case $I = .025$, $E = .8$, $R = 921$ and $r = 1.3$. Substituting these values gives,

$$.025 = \frac{n\,.8}{921 + n\,1.3}$$

Multiplying by $921 + 1.3\,n$ gives

$$23.025 + .0325\,n = .8\,n$$

Transposing $.0325\,n$ gives

$$.8\,n - .0325\,n = 23.025$$

or

$$.7675\,n = 23.025$$

hence,

$$n = 30. \qquad \text{Ans. 30 cells.}$$

Example.— Eight gravity cells (E. M. F. = 1.06, resistance = 3.2 ohms each) are connected in series. Three wires, 21 ohms each, are connected in parallel to the poles of the battery. Find the current.

Solution.— The battery E. M. F. is 8.48 volts, and its internal resistance is

$$8 \times 3.2 = 25.6 \text{ ohms.}$$

The resistance of the three wires in parallel is

$$21 \div 3 = 7 \text{ ohms.}$$

Hence the total current is

$$I = \frac{8.48}{25.6 + 7} = \frac{8.48}{32.6} = .26 \text{ ampere.}$$

Ans. .26 ampere.

QUANTITY, ENERGY AND POWER.

Quantity. The strength of a current is determined by the amount of electricity which passes any cross section of the conductor in a second; that is, current strength expresses the *rate* at which electricity is conducted. The *quantity* of electricity conveyed evidently depends upon the current strength and the time the current continues.

The Coulomb. The coulomb is the unit of quantity, and is equal to the amount of electricity which passes any cross section of the conductor in 1 second, when the current strength is 1 ampere. If a current of 1 ampere flows for 2 seconds, the quantity of electricity delivered is 2 coulombs; and if 2 amperes flow for 1 second, the quantity is also 2 coulombs. With a current of 4 amperes flowing for 3 seconds, the quantity delivered is 12 coulombs. The quantity of electricity in coulombs is, therefore, equal to the current strength in amperes multiplied by the time in seconds, or

$$Q = I \times t$$

where Q is the quantity in coulombs, I the current in amperes and t the time in seconds.

The coulomb is also called the *ampere-second*. The quantity of electricity delivered in 1 hour, when the current is 1 ampere, is called 1 *ampere-hour*. The ampere-hour is equal to 3,600 coulombs, as it is equal to 1 ampere for 3,600 seconds.

From the formula $Q = I\,t$, it follows that

$$I = \frac{Q}{t} \text{ and } t = \frac{Q}{I}.$$

Example.— A current of 18 amperes flows through a circuit for $2\frac{1}{4}$ hours. What quantity of electricity is delivered?

Solution.— Reducing $2\frac{1}{4}$ hours to seconds gives 8,100 seconds, and $8{,}100 \times 18 = 145{,}800$. Ans. 145,800 coulombs.

Energy. Whenever a current flows, a certain amount of energy is expended, and this may be transformed into heat, or mechanical work, or may produce chemical changes. The unit of mechanical energy is the amount of work performed in raising a mass of one pound through a distance of one foot, and is called the foot-pound. The work done in raising any mass through any height, is found by multiplying the number of pounds in that mass by the number of feet through which it is lifted. Electrical work may be determined in a corresponding manner by the amount of electricity transferred through a difference of potential.

The Joule. The joule is the unit of electrical energy, and is the work performed in transferring one coulomb through a difference of potential of one volt. That is, the unit of electrical energy is equal to the work performed in transferring a unit quantity of electricity through a unit difference of potential. It is evident that if 2 coulombs pass in a circuit and the difference of potential is one volt, the energy expended is 2 joules. Likewise if 1 coulomb passes and the potential difference is 2 volts, then the energy expended is also 2 joules. Therefore, to find the number of joules expended in a circuit, multiply the quantity of electricity by the potential difference through which it is transferred. This is expressed by the formula,

$$W = Q\,E, \text{ or } W = I\,E\,t,$$

where W is the work in joules, Q the quantity in coulombs, E the potential difference in volts, I the current in amperes and t the time in seconds.

By Ohm's law $E = R\,I$ and by substituting this value of E in the equation for energy, we obtain the formula,

$$W = I^2\,R\,t,$$

which may be used when the current, resistance, and time are known, R being the resistance in ohms.

Example.—With a potential difference of 97 volts and a current of 14 amperes, what energy is expended in 20 minutes?

Solution.—Work is expressed by the product of the quantity

and potential difference. The time in seconds equals $20 \times 60 = 1200$, and the work $W = 14 \times 1200 \times 97 = 1{,}629{,}600$ joules.

Ans. 1,629,600 joules.

Example. — The resistance of a circuit is .9 ohm, and the current is 25 amperes. What energy is expended in half an hour?

Solution.— Substituting these values of resistance, current and time in the formula $W = I^2 R t$, we have, $W = 25^2 \times .9 \times 30 \times 60 = 1{,}012{,}500$ joules. Ans. 1,012,500 joules.

Power. Power is the *rate* of doing work, and expresses the amount of work done in a certain time. The horse-power is the unit of mechanical energy, and is equal to 33,000 foot-pounds per minute or 550 foot-pounds per second. A certain amount of work may be done in one hour or two hours, and in stating the work done to be so many foot-pounds or so many joules, the rate at which the work is done is not expressed. Power on the other hand, includes the rate of working.

It is evident that if it is known that a certain amount of work is done in a certain time, the rate at which the work is done, or the power, may be obtained by dividing the work by the time, giving the work done per unit of time.

The Watt. The electrical unit of power is the watt, and is equal to one joule per second, that is, when one joule of work is expended in one second, the power is one watt. If the number of joules expended in a certain time is known, then the power in watts is obtained by dividing the number of joules by the time in seconds. The formulas for the work done in joules as given on the preceding pages are,

$$W = I E t, \text{ and } W = I^2 R t.$$

By dividing each of these by the time t, we obtain the corresponding formulas for power as follows:

$P = I E$, and $P = I^2 R$, where P is the power in watts, I the current in amperes, E the potential difference in volts, and R the resistance in ohms.

The power is obtained therefore, by multiplying the current by the voltage, or by multiplying the square of the current by the resistance.

The watt is sometimes called the *volt-ampere*.

For large units the *kilowatt* is used, and this is equal to 1,000

watts. The common abbreviation for kilowatt is K. W. The *kilowatt-hour* is a unit of energy, and is the energy expended in one hour when the power is one kilowatt.

Example.— A 112-volt incandescent lamp has a resistance of 120 ohms. What power is absorbed in the lamp?

Solution.— The current is

$$I = \frac{E}{R} = \frac{112}{120} = .933 \text{ amperes.}$$

The power is $P = EI = 112 \times .933 = 104.5$ watts.

Equivalence of Electrical Energy in Heat Units. Whenever there is any resistance to the flow of a current there is always a certain amount of electrical energy transformed into heat. The current in passing through such resistance expends a certain amount of energy in overcoming the resistance, and this energy is dissipated as heat. The entire electrical energy of a circuit may be transformed into heat or only part of the energy may appear as heat, the remainder being transformed into mechanical or chemical work. The energy which appears as heat raises the temperature of the circuit to an amount depending upon its radiating surface and the temperature of the surrounding medium.

When the resistance of a circuit and the current are known, the electrical energy expended may be calculated by finding the product of the square of the current, the resistance, and the time, as by the formula at the foot of page 36. All this energy is transformed into heat. Other work may be done by the current, as would be the case if an electric motor were connected to the circuit, but this requires additional energy to that which is dissipated as heat. The formula referred to gives only the energy lost as heat, which is the total energy when no other work is done. This formula, which gives the energy in joules, is in accordance with Joule's law, which is as follows:

The number of heat units developed in a conductor is proportional to its resistance, to the square of the current, and to the time the current lasts.

As we have seen, the unit of electrical energy is the joule. The common unit of heat is the calorie, which is the amount of heat necessary to raise the temperature of 1 gram of water through 1 degree Centigrade. By careful investigations it has been found

that the joule is equivalent to .24 of a calorie; that is, one joule of electrical energy when transformed into heat is equal to .24 calorie. Electrical energy may therefore be expressed in heat units by multiplying the number of joules by .24; that is,

$$U = I^2 \times R \times t \times .24$$

where U is the heat in calories and t the time in seconds.

As one joule is equivalent to .24 calorie, it follows that one calorie is equivalent to 4.2 joules approximately.

Because of the units in which it is measured, the calorie is also called the gram-degree. Its equivalent in units, based on the pound and Fahrenheit degree, may be found from the fact that 1 pound is equal to 453.592 grams, and 1 Fahrenheit degree is equal to $\frac{5}{9}$ of 1 Centigrade degree. Therefore, the number of calories required to raise the temperature of 1 pound of water 1° Fahrenheit is

$$\tfrac{5}{9} \times 453.592 = 252 \text{ calories (very nearly).}$$

Example.—How much will the temperature of 4 pounds of water be raised, if a coil of wire of 1.5 ohms in the water carries 20 amperes for 5 minutes?

Solution.—

$$\text{Calories produced} = .24 \times I^2 \times R \times t$$
$$= .24 \times (20)^2 \times 1.5 \times 300 = 43{,}200.$$

$$\text{Pound-degrees produced} = \frac{43{,}200}{252} = 171.4+.$$

Therefore, the temperature of the 4 pounds will rise

$$\frac{171.4}{4} = 42.85° \text{ Fahrenheit.}$$

Ans. 42.85°.

Equivalent of Electrical Energy in Mechanical Units. The common unit of mechanical energy is the foot-pound, and from experiment it has been found that one joule is equivalent to .7373 foot-pound; that is, the same amount of heat will be developed by one joule as by .7373 foot-pound of work.

As one horse-power is equal to 550 foot-pounds per second, it follows that this rate of working is equivalent to

$$\frac{550}{.7373} = 746 \text{ joules per second (approx.).}$$

Hence one horse-power is equivalent to 746 watts. Therefore to find the equivalent of mechanical power in electrical power multiply the horse-power by 746, and to find the equivalent of electrical power in mechanical power divide the number of watts by 746.

Example.— An electric motor takes a current of 196 amperes from a 500-volt circuit. What is the equivalent in horse-power?

Solution.—

$$\text{Watts} = EI = 500 \times 196 = 98{,}000.$$

$$\text{Horse-power} = \frac{\text{watts}}{746} = \frac{98{,}000}{746} = 131+.$$

Ans. 131+ horse-power.

THE SUPPLY OF ELECTRICAL ENERGY.

Electrical energy is now made use of on such a large scale for lighting, power, heating, etc., that it is generated or produced by machines of great capacity. The dynamo is used for this purpose and machines having a capacity of several thousand kilowatts are now common.

Central Stations. Large central stations or power houses are built at convenient places and here are collected the generating, controlling and measuring apparatus. Usually steam engines or turbines are used to drive the dynamos, and from the latter, large copper mains conduct the current to the switchboard located within the station. Here are assembled all the regulating devices, instruments, and switches for the control of the system. From the switchboard conducting mains run out to various distant points, where the energy is to be used, to the receiving apparatus, such as electric motors, lamps, heating devices, etc. A complete system is therefore made up of three sub-divisions — the generating plant, the conducting mains, and the receiving apparatus.

Isolated Plants. Besides large central stations which occupy one or more entire buildings and which are usually built and designed especially for such purpose, there are the comparatively small and simple plants called isolated power plants. They are purely local systems and supply energy to a single building, or to buildings in the immediate vicinity. The generating apparatus in this case is usually located in the basement of the building.

Large hotels and office buildings are frequently provided with individual generating plants.

Losses in Energy. In operating an electrical machine there is always some loss in energy, that is, the machine does not give out an amount of energy equivalent to the amount it receives. Besides ordinary mechanical losses there is in addition the electrical loss, which always occurs when a current flows through any resistance. This loss as previously explained, is equal to the square of the current multiplied by the resistance.

The ratio of the amount of energy which a machine gives out, to the amount which it receives is called the **commercial efficiency** of the machine. For example, if the commercial efficiency of a dynamo is stated to be 80%, then 20% of the energy given to the dynamo is lost, partly in overcoming friction and partly in electrical losses.

Where electricity is transmitted some distance by means of conducting mains, there takes place a loss in the line due to heating, which is frequently as much as 10%. Also at the receiving station, if the electrical energy is converted into mechanical by means of an electric motor, there will be a further loss.

Illustrative Example. For example, suppose it is desired to ascertain the losses in a system which comprises a generator, conducting mains and an electric motor. Suppose the efficiency of the generator is 92% and that 1000 horse-power are imparted to it by the driving engine. The output of the dynamo will be $.92 \times 1000$, or 920 horse-power, and this is equivalent to 920×746, or 686,320 watts. The energy lost in the dynamo will be 80×746, or 59,680 watts. We will assume the voltage of the dynamo and the circuit to be 1000, and as the power in watts is equal to the product of the voltage and current, the current must be $686{,}320 \div 1000$, or 686 amperes approximately.

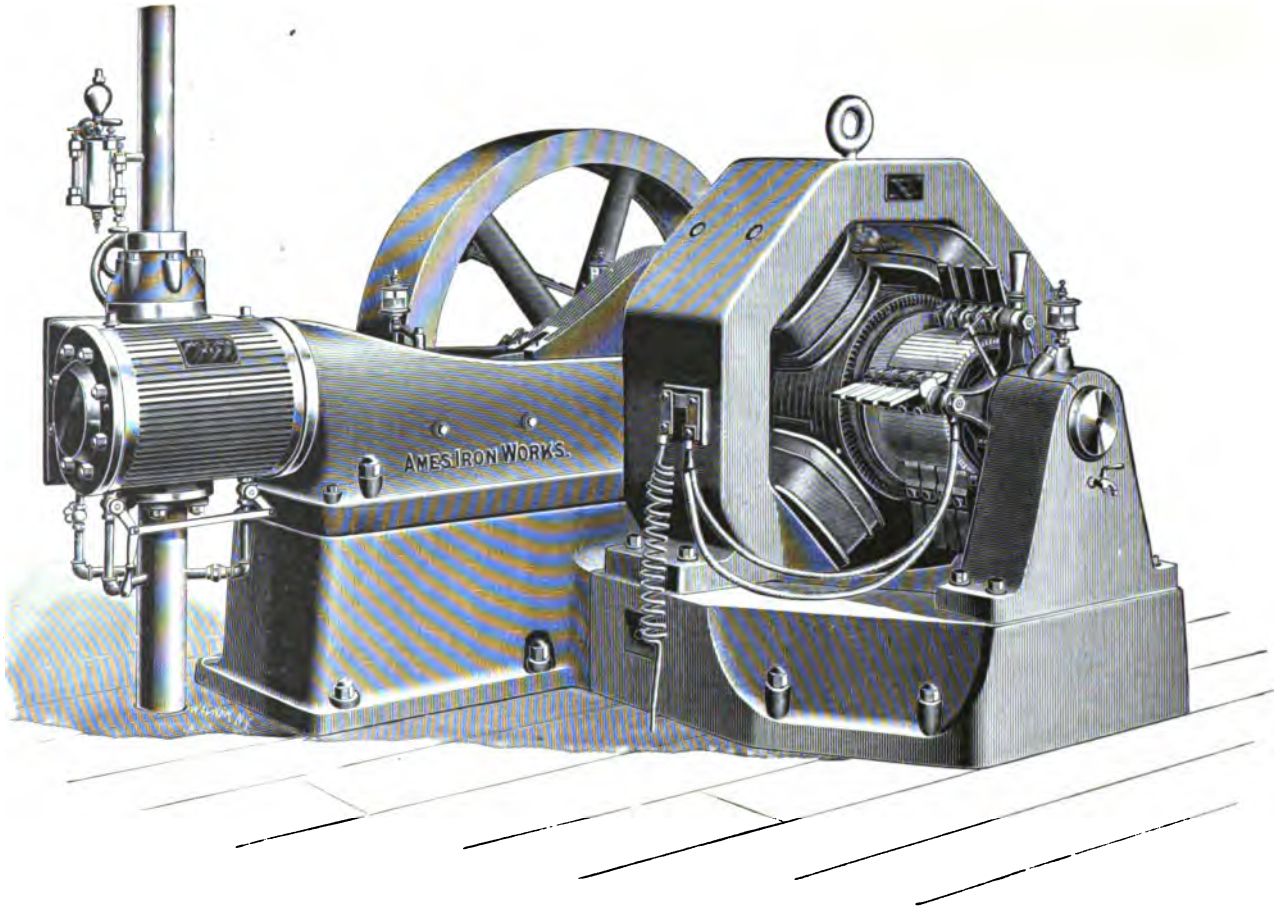
Now suppose the resistance of the conducting mains is equal to .11 ohms. Knowing the current in the mains and the resistance, the loss therein is obtained by applying the formula $I^2 R$ giving $686^2 \times .11$, or 51,765 watts. The energy available at the receiving end of the line will therefore be $686{,}320 - 51{,}765$, or 634,555 watts.

The remaining loss to be considered is that in the electric

motor. Assuming the efficiency of the motor to be 90%, the power lost therein will be .10 × 634,555, or 63,455 watts. The output of the motor is therefore equivalent to 634,555 — 63,455, or 571,100 watts. This in mechanical units is equal to 571,100 ÷ 746, or 765 horse-power approximately.

Hence from an input of 1,000 horse-power at the generating station, the work the motor is capable of performing at the receiving station is 765 horse-power. The efficiency of the entire system under the assumed conditions is therefore 765 ÷ 1,000, or 76.5 %.

Among the great variety of generating machines, systems of distribution and auxiliary devices, each has its particular advantage for special conditions, and the selection of the type of machine and system of distribution depends almost entirely upon the special circumstances. For example, a low voltage system is best adapted for isolated plants, whereas for the transmission of power long distances very high voltages are used. The various types of machines, systems, etc., with their special advantages and disadvantages, will be fully considered in the following sections.



ENGINE DIRECT CONNECTED WITH EDDY GENERATOR

SECTION 3.

THEORY OF DYNAMO-ELECTRIC MACHINERY.

THEORY OF THE GENERATOR.

Definition. - A dynamo-electric machine is a machine in which mechanical energy is converted into electrical energy, or *vice versa*, by means of electro-magnetic induction.

The term *generator* is commonly applied to a machine which converts mechanical energy into electrical energy.

A *motor* serves to convert electrical energy into mechanical energy. The generator and motor are similar in construction, but the operation of one is the reverse of the other. The motor is separately considered in another discussion.

The operation of a dynamo-electric machine depends upon the relation existing between magnetism and the electric current, and the fundamental principles will now be considered.

FUNDAMENTAL PRINCIPLES.

The Magnetic Field. The space surrounding a magnet is subject to its influence, and is called its magnetic field. This influence is exerted in certain definite directions, and its strength and direction are represented by lines of magnetic force. The strength of the field is indicated by the number of magnetic lines per unit area, and is called its density, or magnetic induction.

Fig. 1 represents the field of a permanent magnet, the lines of force passing outside the magnet from the north to the south pole in curved paths. The number of lines per unit of cross-section, and therefore the strength of the magnet, is greatest at the poles.

Magnetic Field of a Conducting Wire. Whenever a current of electricity passes through a conducting wire, the current creates a magnetic field, which surrounds the wire, as shown in Fig. 2. The magnetic lines of this field encircle the wire and have their greatest density near the same, gradually decreasing in effective strength as the distance from the wire increases. These magnetic lines of force represent a form of energy; and, in fact, a considerable

portion of the energy of the current lies in the surrounding magnetic field.

The direction of the magnetic lines about the conductor always bears a definite relation to that of the current. When looking along the wire in the direction of the current, the direc-

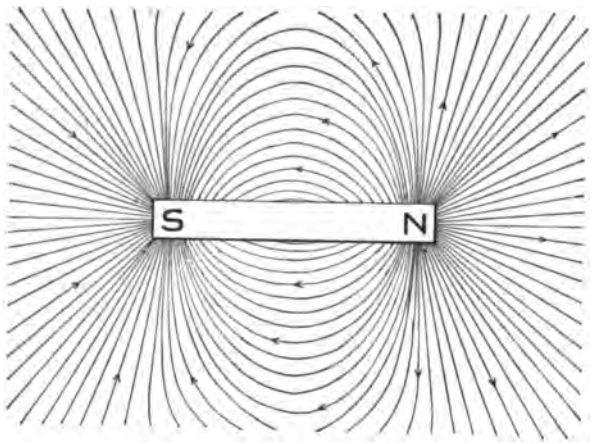


Fig. 1.

tion of the lines of force will always be right-handed; that is, looking at the left-hand end of the conductor shown in Fig. 2, the current being from left to right, the lines of force have the same direction as the hands of a watch.

Field of a Solenoid and Electro-magnet. When a conductor is made in the form of a coil, and a current passed through the same, the lines of force, which would otherwise encircle each turn of the conductor, unite and form a strong magnetic field similar to that of a magnet.

Fig. 2.

The magnetic field of a solenoid is represented by Fig. 3.

When the coil is supplied with a core of soft iron, the effective strength of the magnetic field is greatly increased. Such a combination is called an electro-magnet, and has the properties of a permanent magnet.

The end at which the lines of force leave the iron core and coil is called the north pole, and the end at which the lines enter the

iron core and coil is called the south pole. When a person is facing the south pole, the direction of current in the coil is always in the same direction as the hands of a watch; and when facing the north pole, the current is in the opposite direction to the hands of a watch. This gives a very simple rule for determining the

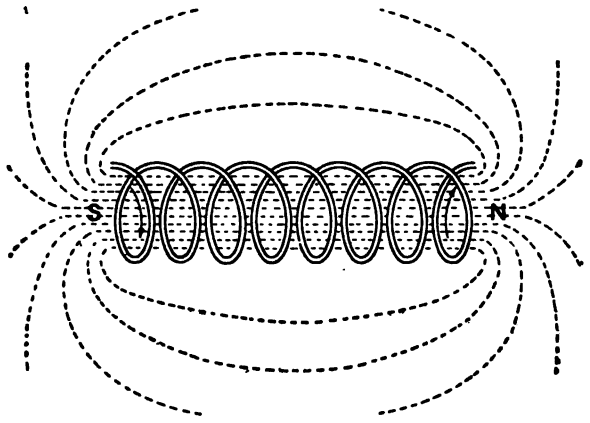


Fig. 3.

relation between the direction of current and polarity of the magnet.

Induced Currents. It would be supposed from the fact that a magnetic field is created by the passage of a current through a conductor, that the reverse action would also take place; that is, the creation of a magnetic field about a conductor would cause the production of a current, and such is found to be the case. The currents created in this manner are called *induced* currents, and are said to be produced by *induction.*

The subject of production of currents by induction is briefly considered in "Elements of Electricity," and the student will note the following facts:

1st. It is only by certain changes of relation between magnetic field and the conductor that the current is produced.

2nd. The change may be due to an increase or decrease in the strength of field about the conductor, and the current flows only while this change in field strength takes place.

3rd. The induced current flows in the opposite direction

when the field strength is increased to that in which it flows when the field strength is decreased.

4th. The change in field strength may be produced by the movement of a permanent magnet, solenoid or electro-magnet in the neighborhood of the conductor, — the source of the field is immaterial.

5th. Relative movement only is necessary, and hence it is immaterial whether the conductor is moved through the field or the field moved across the conductor.

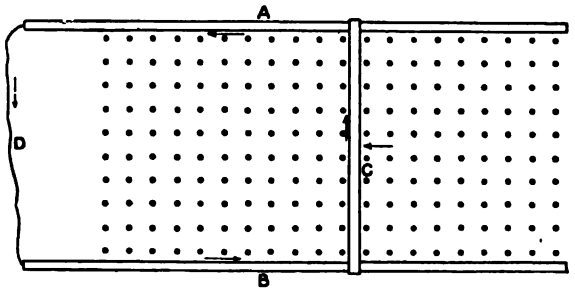


Fig. 4.

6th. The current flows through a closed circuit only as a result of the induced electro-motive force which is first created, and the strength of the current depends upon the value of the induced electro-motive force and resistance of the circuit, in accordance with Ohm's law.

Movement of Conductor Across the Field. We shall now consider more fully the production of E. M. F. and current by movement of a conductor *across* a magnetic field.

In Fig. 4 the dots represent the lines of force of a uniform field, their direction being upward through the paper. *C* represents a conductor which is movable on the rails *A* and *B*, the circuit through *B*, *C* and *A* being completed by the connecting wire *D*. Now when *C* slides along the rails, it cuts across the lines of force, an E. M. F. is induced, and a current flows, as indicated. The movement of *C* across the field causes a difference of potential between its ends, due to the fact that there is a continual cutting of lines of force about the conductor. If the slide *C* were moved endwise, however, no E. M. F. would be generated, as no

lines would be cut, and during such movement there is no relative change of field with reference to the slide. The same would be true if the slide were moved vertically with reference to the paper. The moment there is any *cutting across* of the lines there is an E. M. F. induced. Such induced E. M. F. exists, however, only during the movement of the slide.

Value of Electromotive Force. The magnitude of the E. M. F. generated depends upon the *rate* at which the conductor cuts across the magnetic lines; that is, it depends upon the number of lines cut in a unit of time. If the conductor cuts across the field in a plane perpendicular to the lines of force, as indicated in Fig. 4, the E. M. F. would depend only upon the field area passed over in a unit of time and upon the density of the field. It therefore follows that the rate at which the lines are cut is determined by the *length* of the conductor, its *speed*, and the *strength* of magnetic field.

Taking, for example, the simple conditions of Fig. 4, let L represent the length of slide C, v its velocity, and B the field density, then

E. M. F. *varies as* $L \times v \times B$.

The electric and magnetic units are based upon the metric system, and have been so chosen that when a conductor cuts 100,000,000 lines of force per second, there exists a potential difference between its ends of 1 volt. The unit upon which the volt is based is the potential difference generated by moving a conductor 1 centimeter long at the rate of 1 centimeter per second across a field which has a strength of 1 line per square centimeter. This very small unit would be inconvenient for practical purposes, and so the volt was taken as 100,000,000 times this quantity. Hence it follows that

$$E = \frac{L \times v \times B}{100{,}000{,}000} = \frac{L \times v \times B}{10^8} = L \times v \times B \times 10^{-8}$$

where E = E. M. F. in volts induced in moving conductor;

L = length of conductor in centimeters;

v = velocity in centimeters per second;

B = number of lines of force per square centimeter.

Therefore, having given the length of conductor, the velocity and the field density, the E. M. F. generated may be computed

readily; or if any three of the quantities are given, the fourth may be determined.

Example.— A conductor .6 meter long cuts across a uniform field having a density of 8,000 lines per square centimeter at the rate of 90 meters per minute. What is the voltage generated?

Solution.— Applying the preceding formula, $L = .6 \times 100 =$ 60 cm., $v = \frac{90 \times 100}{60} = 150$ cm., and $B = 8{,}000$.

Substituting these values,

$$E = 60 \times 150 \times 8{,}000 \times 10^{-8} = .72 \text{ volt.}$$

Ans. .72 volt.

Example.— In order to generate a voltage of 1.1 by a conductor 1 meter long, when moving across a uniform field at the rate of 108 meters per minute, what must be the magnetic induction?

Solution.— The known quantities are

$$E = 1.1,\ L = 1 \times 100 = 100,\ v = \frac{108 \times 100}{60} = 180.$$

Substituting these values,

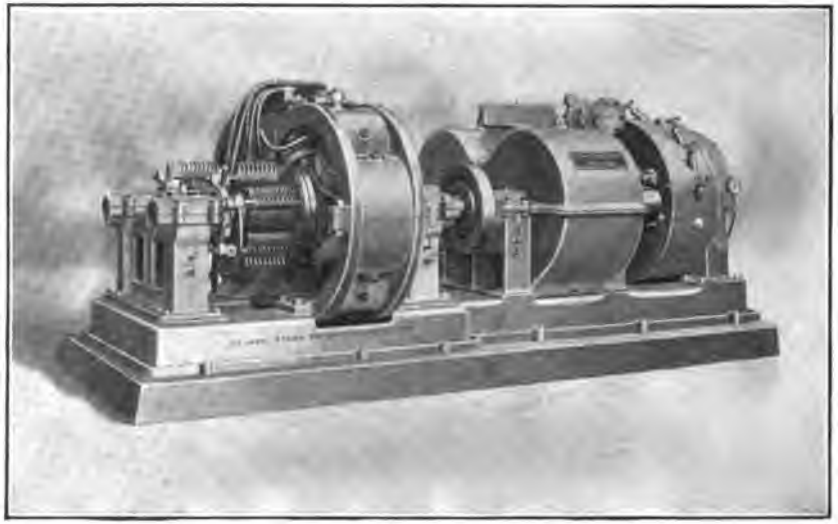
$$1.1 = 100 \times 180 \times B \times 10^{-8}$$

Or,
$$B = \frac{1.1 \times 100{,}000{,}000.}{18{,}000}$$
$$= 6{,}111 +$$

Ans. 6,111 + lines.

Direction of Induced Current. There is a definite relation between the direction of induced E. M. F., or current, the direction of motion and the direction of the lines of force. Referring to Fig. 4, and remembering that the lines of force are assumed to pass upward through the paper, and the slide C to move to the left, the direction of current along C will be that indicated by the arrow. The direction of lines of force, motion and current are all at right angles to each other. If C were moved to the right instead of to the left, the current would flow in the opposite direction to that indicated.

A simple rule for determining the direction of current is the "finger-rule" of Dr. Fleming. This is illustrated in Fig. 5. When the first three fingers of the *right* hand are placed so that they are at right angles to one another, then if the forefinger is



DIRECT-CURRENT TURBINE DYNAMO

pointed in the direction of the lines of force and the thumb in the direction of motion, the middle finger will indicate the direction of induced E. M. F., or current.

For example, if the lines of force were horizontal and passed from left to right and the conductor moved upward in a vertical plane across the lines, the direction of current in the conductor would be away from the observer. Also, if the direction of the lines of force of Fig. 4 were downward through the paper and the slide *C* were moved to the right, the current would still be in the same direction as that indicated. That is, if the direction of both the field and of motion be reversed, then the direction of current remains unchanged. Reversing *either* the field *or* the motion will reverse the direction of current.

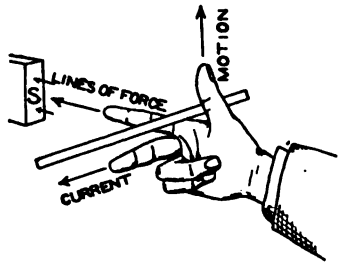


Fig. 5.

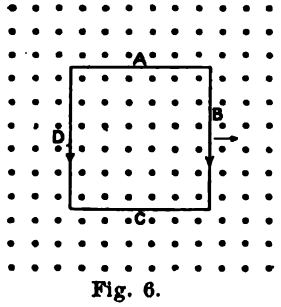


Fig. 6.

E. M. F. in Closed Coil. The E. M. F. is generated in the dynamo-electric machine by movement of coils of wire through a magnetic field. We shall now consider the E. M. F. generated in a closed coil when moved in different ways through a magnetic field.

The dots in Fig. 6 represent a uniform magnetic field passing upward through the paper. *A B C D* represents a closed conducting coil, and let us suppose it is moved to the right, as indicated by the arrow. In such an event, sides *A* and *C* cut no lines of force, and no E. M. F. is generated by them. Side *B*, however, cuts the field, and by applying Fleming's rule it is evident that an E. M. F. is generated in the direction shown by the arrow applied to *B*. Also, as side *D* is subject to the same conditions, an E. M. F. is generated in the same direction as that in *B*, and as each cut the same number of lines of force in

the same time, the E. M. F.'s generated are equal. Sides *A* and *C*, although not effective in cutting the field, serve as connecting conductors for the other sides. It is clear from the figure that the E. M. F.'s in *B* and *D* oppose each other, and therefore no current flows. In a similar manner it may be shown that no current will flow, no matter how the coil is moved, provided it always lies in a plane perpendicular to the magnetic lines. The E. M. F. generated in one part of the coil will always be opposed by an equal and opposite E. M. F. generated in the remaining part.

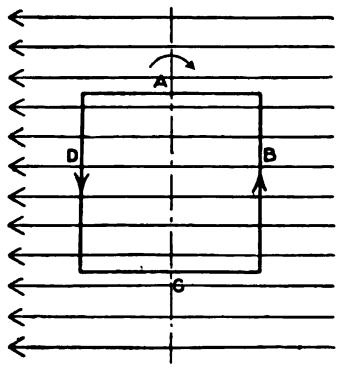


Fig. 7.

When, however, the coil is turned about an axis, the result is different. This may be understood by considering Fig. 7. Here the magnetic lines are represented as passing from right to left, and the coil as being turned about an axis in the direction indicated. The sides *A* and *C* cut no lines of force, and therefore generate no E. M. F. For the position shown, side *B* is moving downward through the paper and cuts directly across the lines and generates an E. M. F. in the direction indicated. Side *D* is moving upward, and therefore generates an E. M. F. in an opposite direction to that in *B*. These two E. M. F.'s, therefore, act in the same direction through the coil, and a current flows; the full E. M. F. of the coil being the sum of that generated by each side. This applies to every position of the coil as it rotates about its axis.

While the coil rotates, the number of magnetic lines passing through it is constantly changing, being a maximum when at right angles to the lines, and being zero when parallel to the lines, as in the position shown in Fig. 7. On the other hand, for the movements referred to when considering Fig. 6, the same number of lines passes through the coil at all times, and it may be stated as a general rule, that an E. M. F. is generated in a closed circuit when the same is moved so that the number of magnetic lines passing through it is altered during the motion.

APPLICATION OF PRINCIPLES TO DYNAMO-ELECTRIC MACHINES.

As an E. M. F. is induced in a conductor only while it moves through a magnetic field, thus cutting the lines, it is necessary for the production of a continuous current to have conductors arranged and interconnected so that some are always effectively cutting the field. This result is attained in the generator by rotating such conductors between the north and south poles of a magnet. We shall first consider a single conductor so rotated.

E. M. F. Induced by Rotating Single Conductor. In Fig. 8 suppose a conductor perpendicular to the paper to revolve with a uniform motion on the dotted circle between the *N S* poles, the field having a uniform density. The right-hand portion of the figure will then represent graphically the varying values of the induced E. M. F., and is called the curve of induced E. M. F.

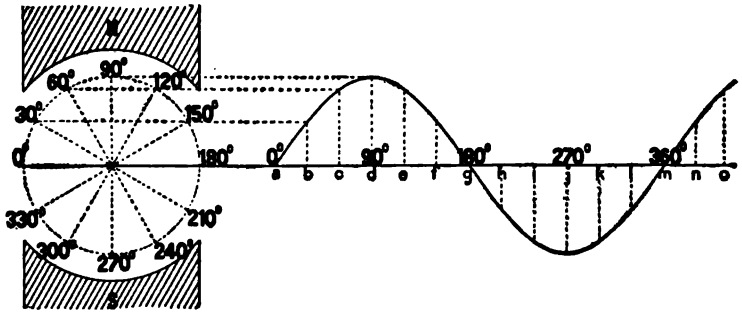
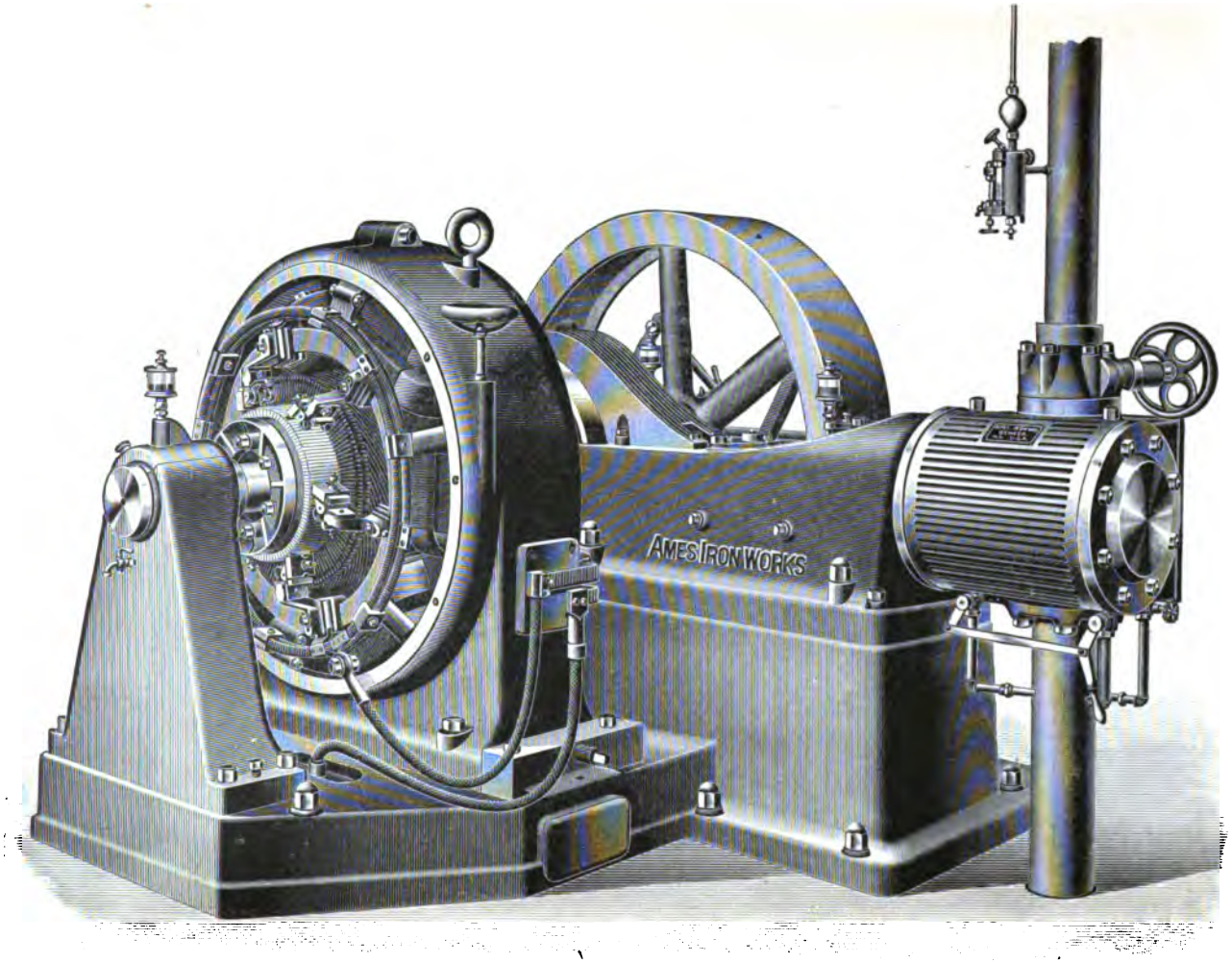


Fig. 8.

The horizontal line is divided into equal parts at points *a*, *b*, *c*, etc., and represent intervals of 30° in the rotation of the conductor. That is, the distance to the curve above or below the line at any point *a*, *b*, *c*, etc., represents the value of induced E. M. F. for the corresponding position of the conductor. For example, when the conductor is at the position 0°, it is then moving *parallel* with the lines of force, and no E. M. F. will be induced. Hence for 0° at *a* the value is represented as zero, which forms the starting-point for the curve. When the conductor has travelled 90° and is opposite the middle of pole *N*, it is cutting directly across the field, and at this time generates the maximum E. M. F. The

curve is therefore at its highest point above *d*. At the intermediate points 30° and 60° between 0° and 90° the E. M. F. gradually increases as represented at *b* and *c*. As the conductor continues to revolve, a less and less number of lines are cut, until at 180° it is again moving parallel with the lines, and no E. M. F. is induced. This condition is represented at *g* where the curve crosses the line. At intermediate points between 90° and 180° the E. M. F. has a gradually decreasing value. After passing the 180° position the conductor again begins to cut a gradually increasing number of lines, but now cuts across them in the opposite direction to that during the first half of the revolution. The E. M. F. induced will therefore be in the opposite direction. Hence at 210° and 240° the E. M. F. gradually increases in an opposite direction, as shown at *h* and *i*. At 270° the maximum E. M. F. is being generated in the reversed direction, as represented at *j*. Upon completion of the 360° of one revolution, the E. M. F. again becomes zero. By continuing the rotation of the conductor the above series of changes will be repeated during each revolution. Hence during each revolution the induced E. M. F. rises from zero to a maximum, decreases, reverses, rises to a maximum in the opposite direction, and decreases to zero again.

Simple Form of Alternating Current Generator. We have seen that when a coil is rotated in a magnetic field, the opposite sides aid each other and the E. M. F. is double that produced by a single conductor. By the use of such an arrangement of a coil a simple form of alternating current machine is created. Fig. 9 represents the arrangement. The coil is mounted so as to rotate between the north and south poles of a magnet. The ends of the coil are connected to copper *collecting rings R R*, mounted on the shaft with the coil but insulated from each other. Upon each ring presses a stationary *brush B*, which is always in contact therewith, and serves to conduct the current to an outside circuit *W*. A complete circuit is then made up from one brush through the external wire *W* to the other brush, then to its collecting ring, through the coil to the other collecting ring, and to the first brush again. The alternating current produced by the rotation of the coil will then pass to the external circuit through the collecting rings and brushes, and during one-half of a revolution the current



ENGINE CONNECTED TO GENERATOR

will pass in one direction and during the remaining half in the opposite direction. The current in the external circuit is available for doing work, and may be passed through motors, lamps, heating appliances, etc.

The Commutator. For the purpose of producing a direct current from the alternating current induced by a rotating coil, a device called a *commutator* is necessary. Its simplest form is shown in Fig. 10, and consists of a split copper ring, the two *segments* of which are insulated from each other, and each segment is secured to one end of the rotating coil. Although an alternating E. M. F. is induced in the coil, by the use of the commutator the current in the external circuit is always in the same direction. This may be understood from Fig. 10.

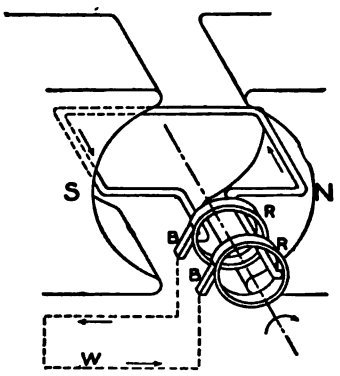


Fig. 9.

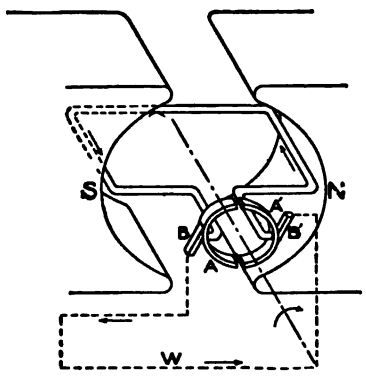


Fig. 10.

For the position of the coil shown, its current will be in the direction indicated and will pass to segment A, brush B, through the external circuit to brush B' and segment A' to the coil. As the coil continues to rotate, the E. M. F. gradually decreases, until when 90° from the position shown, the E. M. F. is zero. At this time the segments are located so that the brushes are about to break contact with one segment and make contact with the other. Further rotation induces an E. M. F. in the opposite direction, but the segments have then passed from one brush to the other, and the direction of current in the external circuit therefore remains unchanged. That is, when the current in the coil is in the direction indicated, segment A will *deliver* current to brush B,

but when in the opposite direction segment *A* will be under brush *B'* and *receive* current from it. The commutator therefore serves to change the direction of the alternating current in the coil to a direct current in the external circuit.

Form of Curve. The curve of induced E. M. F. in the external circuit when a two-part commutator is used is shown in Fig. 11, and is the same as that in Fig. 8, except that the negative portion of the curve is turned above the horizontal. The direction of the current is always the same, but rises to a maximum and falls to zero twice during each revolution, giving what is called a *pulsating* current. It must be remembered, however, that the form of curve shown is the theoretical curve, with the assumption that the speed is constant and the field density uniform. With the actual machine, of course, the conditions are modified more or less, and other considerations, such as self-induction and distortion of the field, materially alter the form of the curve.

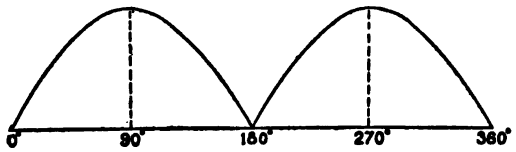


Fig. 11.

The coil, instead of consisting of a single turn, may be made up of two or more, as shown in Fig. 12. The sum of the electromotive forces induced in each turn is the resultant E. M. F. of the coil. Hence if there are n turns, the resultant E. M. F. will be n times the E. M. F. induced in one turn.

Owing to the fact that a pulsating current is generally undesirable for practical work a two-part commutator is now seldom used. The current is rendered nearly constant in value, however, by the use of several coils and a commutator made up of a corresponding number of segments. The coils are interconnected so that the E. M. F. induced in each is added to that of the others. The various methods of connecting will be considered on following pages, and only the principle will now be considered.

Suppose we have two coils at right angles to each other revolving in a magnetic field, and connected in such manner as to assist each other and yield a direct current to the external circuit. Then, while the maximum E. M. F. is induced in one coil, no

E. M. F. will be induced in the other, and at intermediate points there will be gradual changes. In Fig. 13 the dotted lines indicate the E. M. F.'s induced separately in the two coils, one being 90° in advance of the other. The combining of the two curves produces the curve in full lines, which is formed by taking the sum of the dotted curves. The upper curve therefore represents the fluctuation in E. M. F. of the combined coils, and it is evident that the amount of fluctuation is greatly reduced. In a similar manner it may be shown that a further increase in the number of coils, spaced uniformly, will cause less and less fluctuation, and by using 30 or more coils, a practically constant current may be obtained.

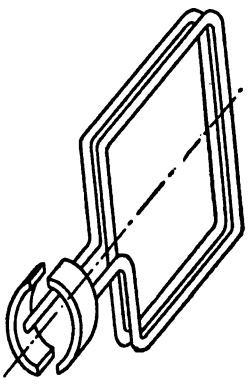


Fig. 12.

Parts of the Generator. Fig. 14 illustrates the essential elements of a generator, which consist of two principal parts,—the stationary *field magnets* and the *armature* which revolves between the poles. A current is passed through the winding around the *cores F F*, to produce the magnetic field in which the

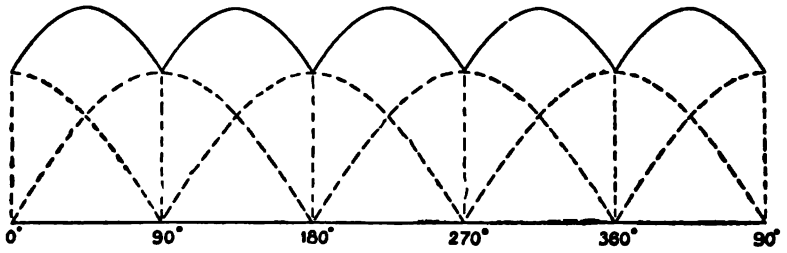


Fig. 13.

coils may rotate. A path for the magnetic lines is provided by the iron cores *F F*, the *yoke Y*, the pole pieces *N S* and the armature as indicated by dotted lines. The armature is made up of the coils and a soft iron core which serves to conduct the magnetic lines. All the coils are interconnected by means of the *commutator C*. The brushes *B B* press lightly upon the commutator and conduct the current to the external circuit, as has been pre-

viously explained. The brushes are made adjustable and are carried by *brush-holders* on a *rocker* or *ring* provided for the purpose.

Frequently, and in all large machines, more than two poles are used. Fig. 15 illustrates the magnetic circuit of a dynamo with four poles. Machines having two poles are called bipolar machines, while those with more than two poles are called multipolar. Some machines have as many as 32 poles. The magnetic circuit is always of such form and construction as to produce a strong field in which the armature rotates. For this purpose it is desirable to have the length of the magnetic circuit, or the distance through which the lines of force pass, as short as possible. The material of this circuit is soft iron or soft steel, in order that the field may have great density.

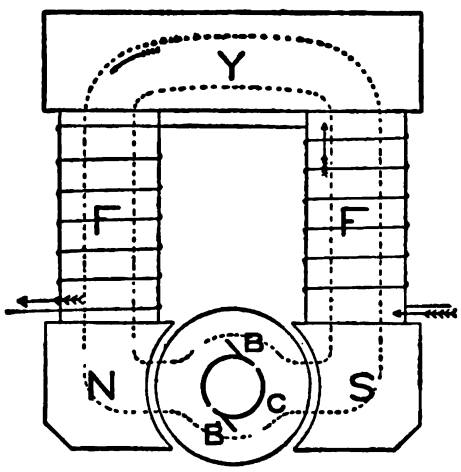


Fig. 14.

Referring to Fig. 14, it will be seen that the magnetic lines pass through the yoke, field cores and pole pieces, then pass across air spaces, called the *air gaps*, and then through the armature core. The armature core is sometimes in the form of a drum and sometimes in the form of a ring, and is always made of very soft sheet iron or soft steel. Since the magnetic lines pass through air with great difficulty compared with the ease of passing through iron, the air gaps are always made as small as mechanical considerations will permit.

The armature is composed of the core above mentioned and the copper coils or windings about the core. The core serves to conduct the magnetic lines from one pole piece to the other; it is mounted upon a supporting frame of cast iron which is firmly secured to the driving shaft and therefore rotates with it. The

shaft is usually supported in self-oiling and self-aligning bearings, and must be constructed so that the armature will always be centered between the pole pieces.

Energy Required to Drive the Dynamo. Although there is no mechanical resistance to the rotation of the armature except friction, the mechanical energy required to drive the armature varies with the amount of electrical energy obtained. When no current is delivered, the armature may be easily rotated; but as soon as a current flows, it reacts upon the magnetic field and opposes the rotation, and the greater the current, the greater the energy necessary to drive the machine. The amount of energy necessary to rotate the armature therefore increases as the load put upon the machine increases.

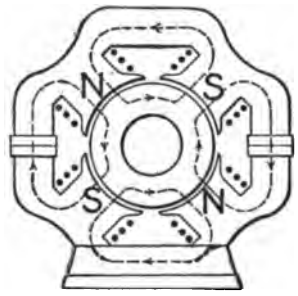


Fig. 15.

ARMATURE WINDINGS.

There are two distinct types of armature windings; one is called the *closed coil* and the other the *open coil* winding.

In the closed coil winding, all the conductors are interconnected so as to form an endless winding, consisting of two or more branches connected in parallel. In the open coil winding the conductors are joined in groups, each group containing in series all conductors which have a similar position with reference to the field. The current is supplied to the external circuit only from those groups which are generating the highest E. M. F.; all other groups being cut out of the circuit temporarily.

Armature windings may also be divided into *ring* and *drum* windings. In the first, the conductors are wound upon and in the form of a ring; in the second they are wound longitudinally upon a cylinder or drum. Open coil windings are used only in special types of machines, such as those for arc lighting; closed coil windings are used in machines for such common purposes as incandescent lamps, power and heating.

Closed Coil Ring Windings. The ring winding is the simplest, and therefore will be first considered.

Figs. 16 and 17 represent a four-coil Gramme or ring winding having a four-part commutator, and consisting of four coils wound about the iron core, with the junction of the coils connected to the commutator bars. The magnetic lines from the north pole pass to the iron core and then to the south pole, as indicated by the dotted lines, there being no magnetic lines across the space enclosed by the ring. Hence as the armature rotates, the conductors on the exterior surface of the ring cut across the magnetic lines twice during each revolution, while the conductors within the ring merely serve to connect the outside conductors in

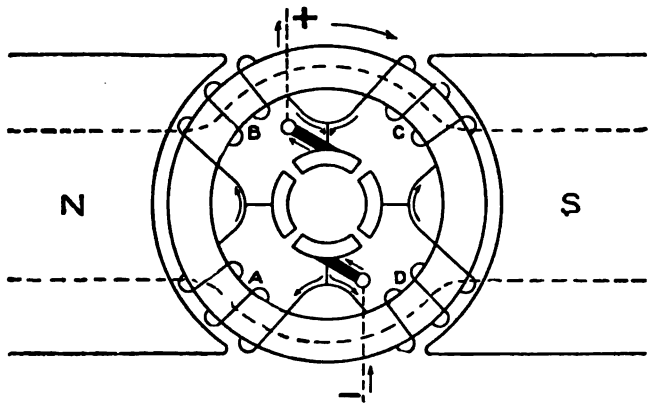


Fig. 16.

series, and are not effective in generating E. M. F. Each coil in Figs. 16 and 17 is made up of three external conductors, and therefore the E. M. F. of each coil will be three times that of a single conductor.

In Fig. 16 coils *A* and *C* are shown as having partly entered the magnetic field, and coils *B* and *D* about to pass out of the field. The path of the current is indicated by the arrows and passes from the external circuit to the lower brush and one bar of the commutator; it then divides and passes through coils *A* and *B* in series on the left, and coils *D* and *C* in series on the right; it then unites, passing to the upper commutator bar and upper brush to the external circuit. As there are two coils in series, the total E. M. F. will be the sum of the E. M. F.'s of the two coils for this position.

Fig. 17 shows the position after the armature has advanced 45° from that shown in Fig. 16. Coils *A* and *C* are then generating the maximum E. M. F., and the current passes from the lower brush through coils *A* and *C* in parallel to the upper brush. Coils *B* and *D* are in what is called the "neutral position," and generate no E. M. F.; in fact, they are temporarily *cut out* of the

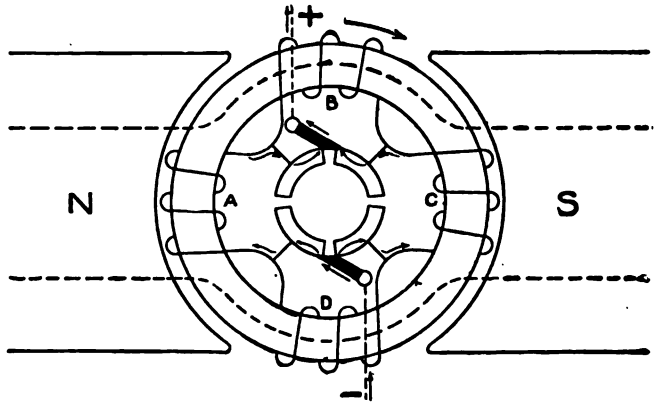


Fig. 17.

circuit, the commutator bars and brushes forming direct connections between coils *A* and *C*. Coils *B* and *D* are said to be *short-circuited;* that is, there is a direct connection of low resistance between the ends of these coils by the commutator bars and brushes, and no current will then pass through the coils.

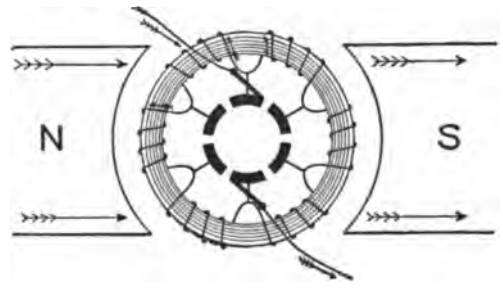


Fig. 18.

Upon further rotation, coils *B* and *D* will pass to the other side of the brushes and they will then generate an E. M. F. in the opposite direction.

Fig. 18 shows a ring-wound armature with six coils and as shown, the current divides, passing through the two halves of the winding in parallel. All the coils on one side are in series, and

each add their portion to the total E. M. F.; the greater the number of coils, the less will be the fluctuation in the current, as explained on page 15. The E. M. F. of each coil varies at different positions, and the E. M. F. generated by some of the coils is increasing, while that of others is decreasing. The total E. M. F., however, remains practically constant when thirty or more coils are used.

Fig. 19 shows a ring winding for a machine with four poles. The winding is the same in form as for a bipolar machine, but the number of brushes and number of circuits through the armature is doubled. Therefore there are two positive brushes and two negative brushes. The two positive brushes are electrically united and connect with the positive wire of the external circuit, while the two negative brushes are united and connect with the negative wire of the external circuit. The current divides at each of the negative brushes, passing in parallel through four circuits (two for each brush) to the positive brushes.

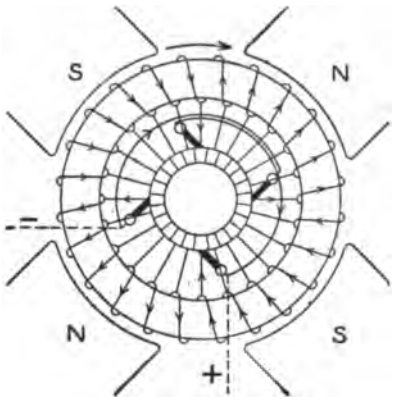


Fig. 19.

For machines with a larger number of poles, there would be a corresponding increase in the number of circuits through the armature.

The number of pairs of brushes may also be correspondingly increased or there may be but one pair since all terminal sections of the same sign (+ or —) can be soldered together.

Closed Coil Drum Windings. Drum windings are distinguished from ring windings in that all wires of the drum armature are distributed over the outside surface of the core. The winding forms a cage which envelops a cylindrical iron core. In the ring armature a large portion of the winding merely serves as connecting leads for that part which lies on the exterior of the core. In the drum armature, however, the only conductors serving as

connectors are at the ends of the cylinder, and therefore a very different form of winding is necessary.

In the ring winding, adjacent conductors are connected directly in series with each other by looping around the ring core, but in the drum winding the return portion of the loop must lie on the exterior of the core, and in order that the E. M. F. induced in each part shall aid the other, the return portion must lie under a pole of opposite polarity to that under which the forward portion lies, as in Figs. 9 and 10.

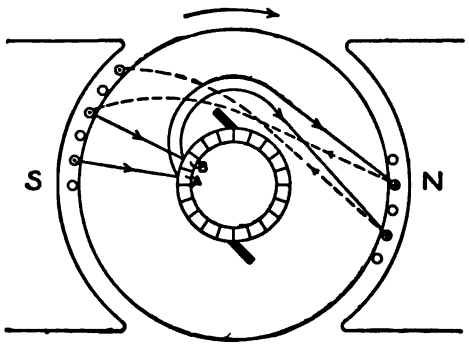


Fig. 20.

The current in passing through the armature from brush to brush must gradually progress through each turn in series. Fig. 20 illustrates a portion of a drum winding, only two complete turns being shown. The small circles represent end views of conductors on the surface of the armature. The crosses and dots indicate the direction of current, the cross representing the tail of a retreating arrow and the dot the head of an approaching arrow. The current gradually progresses from bar to bar of the commutator as indicated by the arrows. The current passes to bar *A* from a conductor at the left of the core, under the influence of the south pole, then by a spiral connector to a conductor under the north pole, thence by a spiral connector at the back end of the core to a conductor under the south pole to bar *B*, then by a spiral connector to a conductor under the north pole, etc. It will be noticed that only the alternate conductors are connected in series, but the intermediate conductors are connected in series with each other to the right-hand half of the commutator.

In order to make all end connectors of the same length and form, the commutator is usually turned 90° in advance of the position shown in Fig. 20, giving an appearance as in Fig. 21. This causes brushes of drum-wound machines to

be opposite the poles instead of between them as in ring-wound machines.

Fig. 22 gives an end view of a complete drum winding in which there are ten complete turns and ten commutator bars. The windings form two circuits in parallel from brush to brush, as may be seen by tracing out the paths of the current. All parts of the winding are similar to each other, and a portion, called an *element*, is made in heavy lines to show clearly the general shape of the turns.

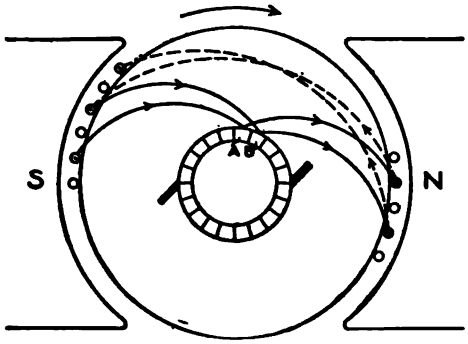


Fig. 21.

Fig. 23 shows a form of drum winding for a four-pole machine with fifteen turns and fifteen commutator bars. It will be seen from the figure that there are four separate circuits between the brushes, two being in parallel from each brush to the other.

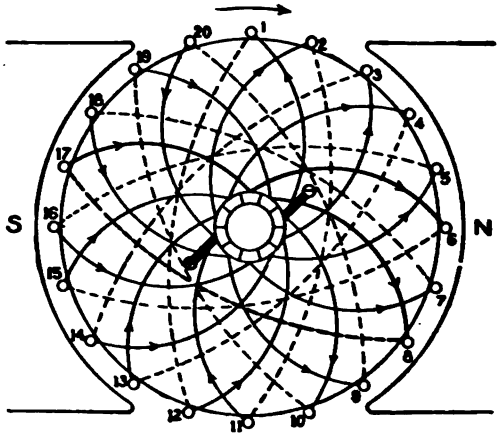


Fig. 22.

Open Coil Windings. Open coil windings are similar to closed coil, except that there are no end connectors between the commutator bars; each coil being alternately cut in and then out of the circuit. Such a winding of four coils with four commutator bars is shown in Fig. 24. The opposite coils are connected in series and each pair of coils alternately make connection with the brushes.

In General. Only the simplest forms of winding of the

different classes have been considered on the preceding pages, and these were illustrated with figures showing a small number of turns. In the actual machine, however, the number of turns is much larger, and there are also a great variety of windings under each type, many of which are equivalent electrically but allow considerable variation in the mechanical construction. The number of

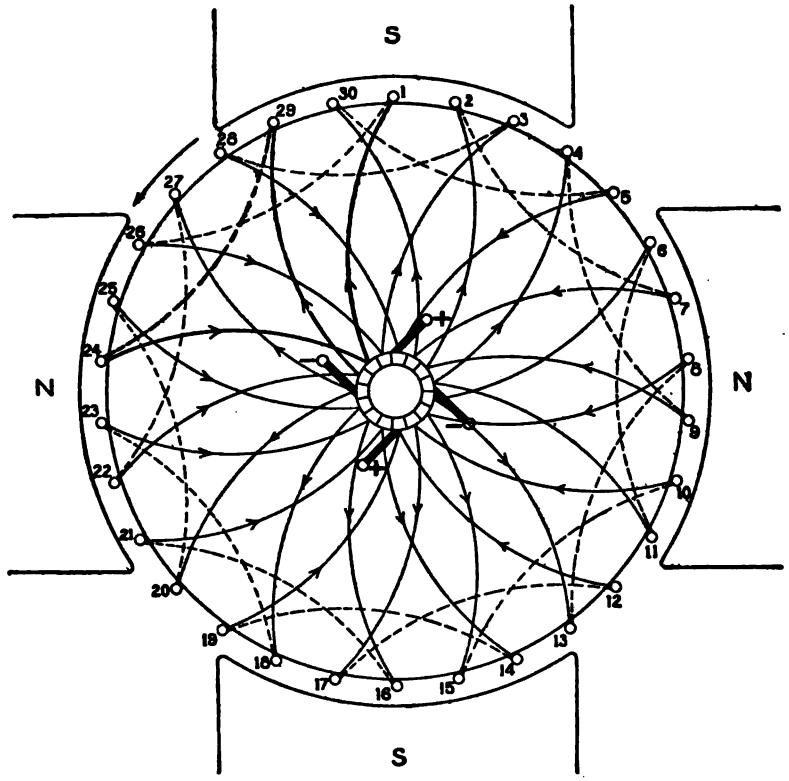


Fig. 23.

poles and the number of brushes used also permit the connecting of the conductors in a variety of ways.

Calculation of E. M. F. Referring to page 7, it is seen that the value of E. M. F. in volts generated by a conductor moving in a uniform field is given by the formula,

$$E = \frac{L \times v \times B}{10^8} = L \times v \times B \times 10^{-8}$$

in which L is the length of the conductor in centimeters, v the velocity in centimeters per second and B the field strength in lines of force per square centimeter.

From the above formula we can arrive at the voltage of the actual machine. By reference to the figures showing armature windings, it appears that a single armature conductor is opposite a pole, and therefore *active* in cutting lines of force only during certain periods of each revolution. The field opposite a pole is practically of uniform strength, and when a conductor is not

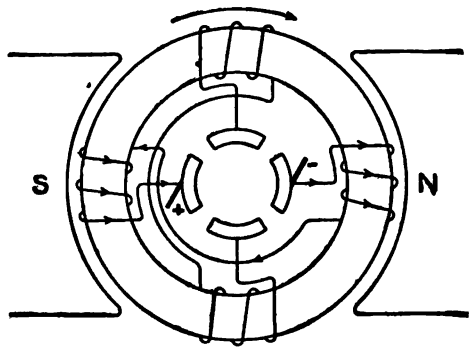


Fig. 24.

under a pole it is not effective in generating any E. M. F. Furthermore, there are usually two or more circuits through the armature connected in parallel, and the voltage of the machine will, of course, be the voltage of each circuit. For bipolar machines there are two circuits connected in parallel, and for multipolar machines there are usually as many circuits in parallel as there are number of poles, although the windings may be varied and interconnected in multipolar machines so that the number of circuits in parallel may be different from the number of poles.

The voltage of any machine will therefore depend upon the number of conductors in series from brush to brush. For a bipolar machine, this will be one-half the total number of conductors on the surface of the armature. Of this one-half only those conductors opposite the pole piece are active. The voltage of such a dynamo will therefore be equal to the E. M. F. generated by a single conductor multiplied by one-half the total number of conductors, multiplied by that percentage opposite the

pole pieces. This percentage is usually from 70 to 80. This may be expressed by a formula as follows,

$$E = \frac{L \times v \times B \times \frac{N}{2} \times p}{10^8} = \frac{L \times v \times B \times N \times p}{2 \times 10^8}$$

in which L, v and B equal the quantities previously given, N the number of conductors on the surface of the armature and p equals the percentage of conductors opposite the pole pieces.

Example. A bipolar machine has 800 surface conductors, each 12 centimeters long, and the percentage opposite the pole pieces is 80. The speed is 1,200 revolutions per minute and the diameter of armature is 40 centimeters. The field density opposite the pole pieces is 3,000 lines per square centimeter. What is the voltage of the machine?

Solution. For this case $L = 12$, $v = 3.1416 \times 40 \times \frac{1200}{60} = 3.1416 \times 40 \times 20 = 2513.28$, $B = 3{,}000$, $N = 800$, and $p = .80$.

Hence,

$$E = \frac{12 \times 2513.28 \times 3000 \times 800 \times .80}{2 \times 10^8} = 289.529 \text{ approx.}$$

Ans. 289.529 volts.

Example. What field density is necessary for a bipolar machine, in order to give a voltage of 220 at 900 revolutions per minute? The armature has 400 surface conductors, is 30 centimeters in diameter and 16 centimeters long, the percentage opposite the pole pieces being 74.

Solution. Here $E = 220$, $L = 16$, $v = 3.1416 \times 30 \times \frac{900}{60} = 1413.72$, $N = 400$, $p = .74$, and B is to be found.

Hence,

$$220 = \frac{16 \times 1413.72 \times B \times 400 \times .74}{2 \times 10^8}$$

or $$16 \times 1413.72 \times 4 \times 74\, B = 2 \times 10^8 \times 220$$

$$B = \frac{2 \times 10^8 \times 220}{16 \times 1413.72 \times 4 \times 74}$$

$$= 6{,}571 \text{ approx.}$$

Ans. 6,571 lines per sq. cm.

The formula on page 25 may be altered slightly to give the voltage of any machine, depending upon its winding. For example, for a four-pole machine with four circuits in parallel

through the armature, the voltage will be that generated by one-fourth of the surface conductors, and the formula becomes,

$$E = \frac{L \times v \times B \times N \times p}{4 \times 10^8}$$

It must be remembered that N equals the total number of surface conductors on the armature. For a ring-wound armature N would be equal to the number of turns, and for a drum-wound armature N would equal twice the number of turns.

Factors Determining Voltage. From the preceding it is clear that the voltage of a dynamo depends mainly upon three factors: speed, field strength, and length and number of conductors on the armature. The voltage may be increased by increasing any one of them. The speed of a machine is limited by mechanical considerations, and low speeds are greatly favored for this reason, and also to enable the driving engine and the generator to be directly coupled. The voltage obtained by using a large number of armature conductors is limited by troublesome sparking at the brushes, and the cost is also greatly increased. A high field strength is obtained by having large and powerful field magnets. A strong field greatly increases the weight of the machine and also increases the cost of the iron and field winding, but is advantageous on account of good regulation and reduction of sparking.

It must be remembered, however, that the formulas given above are for the theoretical values only, and these are somewhat reduced by armature reactions which will be considered on the following pages.

THE FIELD.

Magneto-Dynamo. The field of early forms of dynamos consisted of permanent magnets, and such machines were called *magneto-dynamos*. These were objectionable on account of their great weight (a very large magnet being necessary to give even a feeble field) and also on account of the gradual decrease in strength due to vibrations and inability to control the same. Very small machines of this type are still in use for light

work, such as ringing telephone bells, but larger machines have been replaced by those having electro-magnets.

Ampere-Turns. The necessary magnetization of the wrought iron, cast steel and cast iron, which is used for the field frames of dynamos is produced by passing a current through the windings upon the frame, and the strength of the field depends upon the number of turns in the coils and strength of current passing through them. In fact, the magnetizing force is proportional to the product of the number of turns in a coil and the strength of its current. This product of number of turns and the current in amperes is called the *ampere-turns*. As far as the amount of magnetization is concerned, it is immaterial how the number of turns and current strength are related to each other as long as the product is the same. That is, it makes no difference whether there are 25 turns with 2 amperes, or 10 turns with 5 amperes; the product is 50 ampere-turns.

Saturation of Magnets. There is a great difference between the relation of the ampere-turns or magnetizing force and the field strength produced thereby for different values in the magnetizing force. When the number of ampere-turns is small, the magnetization of the iron will increase rapidly for a small increase of magnetizing force, and as the ampere-turns become greater, the resulting field strength increases almost in direct proportion. The increase is not, however, in direct ratio. This rapid increase in field strength continues to a certain point and then the increase begins to be less and less for an equal increase in ampere-turns, until finally a great increase in ampere-turns produces practically no increase in field strength. The iron is then said to be *saturated*, or to be in a state of *magnetic saturation*. An increase in the magnetizing force when this point is reached is, of course, of no advantage, and results simply in a waste of energy.

Fig. 25 shows graphically the relation between the magnetizing force and the corresponding field strength for a sample of wrought iron. In this plot the abscissae or horizontal distances represent the magnetizing force H in ampere-turns, while the ordinates or vertical distances represent the field strength or induction B, in number of lines per square centimeter. The small circles on the curve represent the points obtained by experi-

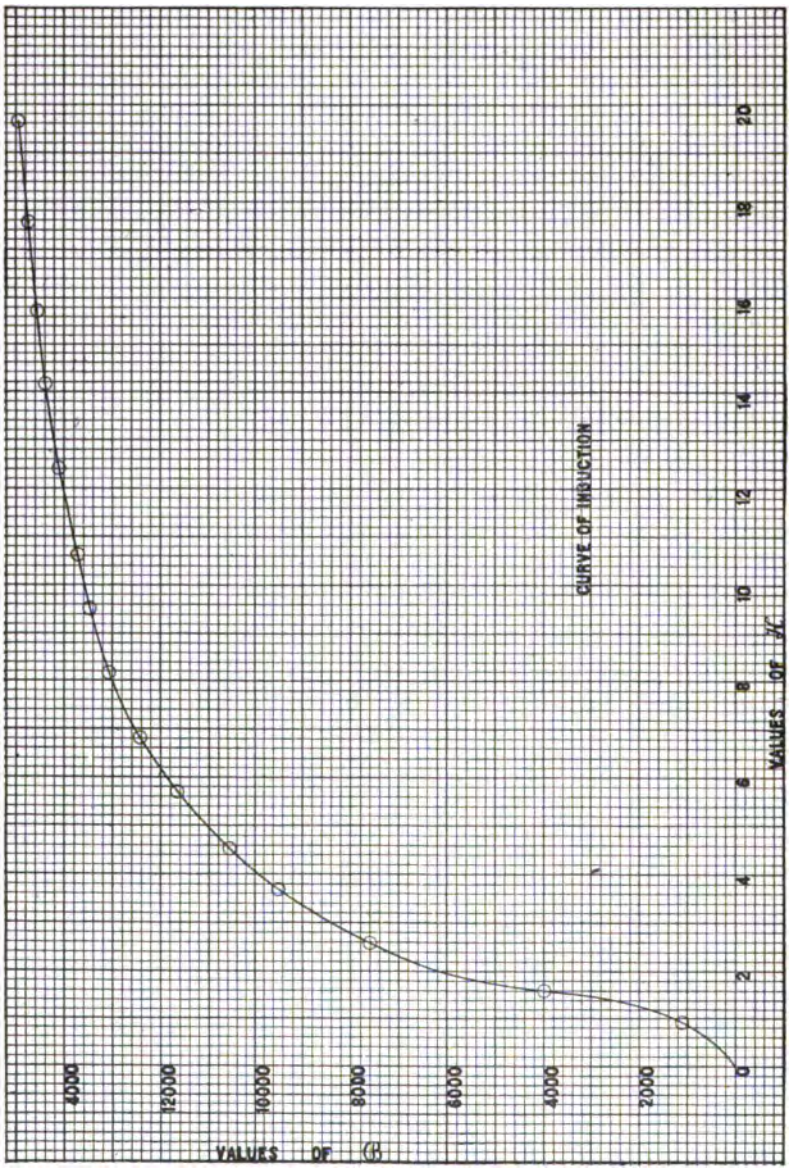

CURVE OF INDUCTION
VALUES OF $\mathcal{H}$.
VALUES OF $\mathcal{B}$
0
2000
4000
6000
8000
10000
12000
14000
2
4
6
8
10
12
14
16
18
20

Fig. 25.

ment, and by means of which the curve is obtained. It appears from the curve that an increase in magnetizing force from 0 to .5 does not increase the magnetic induction nearly as much as does the increase from .5 to 1.0, showing that it requires some little force to move the molecules from their irregular position into the more symmetrical arrangement which they are supposed to assume when magnetized. The value of the field strength is about 1,300 lines per square centimeter for 1 ampere-turn, and is 9,900 for 4 ampere-turns, showing the increase to be very rapid. For 8 ampere-turns the field density is 13,000 lines, showing the proportional increase to be much less for the field density than for the magnetizing force, and beyond this point the increase in field

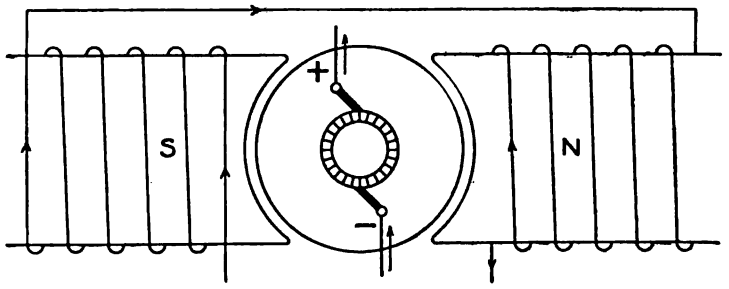


Fig. 26.

strength becomes gradually less and less, until the curve approaches a straight horizontal line, when the iron is saturated.

Types of Field Windings. There are four different types of field windings depending upon the method of excitation, giving rise to the following four classes of dynamos:

1. The *separately excited* dynamo.
2. The *series* dynamo.
3. The *shunt* dynamo.
4. The *compound* dynamo.

Each will now be briefly considered in the order named.

Separately Excited Dynamo. A separately excited dynamo is one having its field coils excited from some outside source, such as a battery or another dynamo. Fig. 26 represents such a machine, the two poles being excited by an outside current, and the current from the armature being available for supplying lamps,

motors, etc. In the separately excited machine the field excitation may be maintained nearly constant irrespective of the change in load put upon the dynamo, but it requires an outside current supply. There are but few direct current machines having separate field excitation, but on account of the nature of the current derived from alternating current machines they are usually separately excited. A small direct current dynamo called its *exciter* is used for this purpose.

The Series Dynamo. We now come to consider dynamos which are self-exciting; that is, they supply their own field current and are therefore self-contained. Of these, the simplest is the series dynamo or *series-wound* machine, and in this type the main

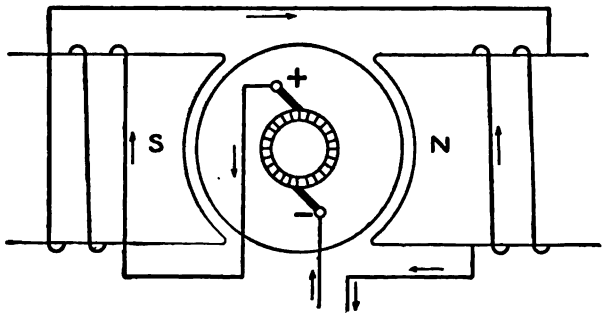


Fig. 27.

current from the armature is passed through the field coils and then to the external circuit. Such a connection is represented in Fig. 27. As these coils carry the main current of the machine they are of comparatively large size, but owing to the large current, only a small number of turns are required to give the necessary magnetization.

The series dynamo has the disadvantage that it cannot be made to start action until a certain speed has been obtained, unless the resistance of the external circuit is below a certain limit. Furthermore, the dynamo requires a special regulator to control the current and voltage with change of load, and about the only practical use for which it is adapted is for operating arc lights.

Shunt Dynamo. In the shunt dynamo or *shunt-wound* machine, the current from the armature has two paths through

which to flow. One is through the external circuit and the other is through the field coils. The connections are represented in Fig. 28. The current from the armature divides at the positive brush and passes through the external circuit to the negative brush, and also through the shunt windings to the negative brush,

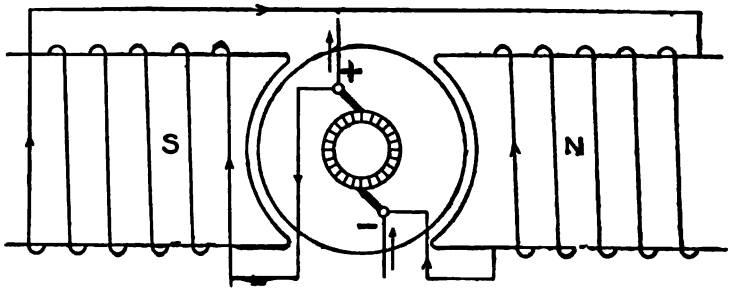


Fig. 28.

the field coils acting as a shunt to the external circuit. In this machine the field windings consist of many turns of fine wire, and take only a small part of the current from the armature; they

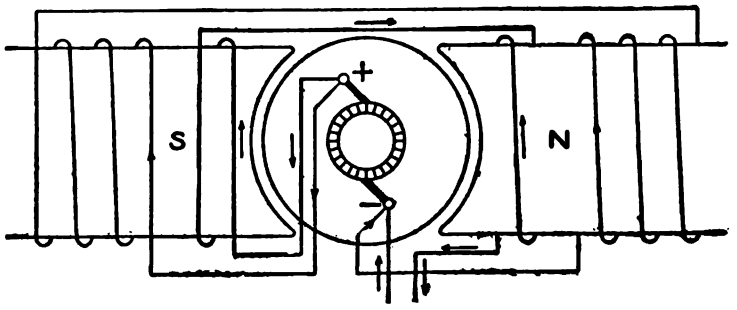


Fig. 29.

differ greatly from the series machine where there are but few turns carrying a large current.

The shunt-wound machine is much better adapted for practical service, such as lighting, and for supplying current to motors, than the series machine, but has been largely replaced by the machine next to be considered.

Compound Dynamo. The compound dynamo or *compound-wound* machine is a combination of the series and shunt windings.

The connections are shown in Fig. 29. In addition to the shunt winding connected from brush to brush, the main current is also passed through a few turns of large wire in series with the external circuit. With this arrangement the disadvantages of the shunt machine are overcome, and a machine which requires almost no attention during changes in load is produced; that is, the machine is practically self-regulating, and is used almost entirely for supplying current for incandescent lighting and power.

The action of the above considered machines is more fully considered in a following section.

Self-Excitation. As the energy required to excite the field magnets is a very small part of that which the machine is capable of supplying, it is evident that after a machine is once running there is no difficulty in maintaining the field strength. The question naturally arises as to the production of current at starting. This is explained by the fact that iron, after it is once magnetized, retains a certain amount of magnetism after the magnetizing force is withdrawn; this is called *residual* magnetism. Hence as the armature is rotated within this weak field, a slight E. M. F. will be generated which is sufficient to supply a feeble current to the field windings. This increases the field strength slightly, which in turn still further increases the E.M.F., and so on until the maximum voltage is attained. This action is called *building up*.

ARMATURE REACTIONS.

On the preceding pages we have considered the fundamental principles upon which the generator is based, and also its general construction. We shall now look into some of the important actions taking place during the operation.

We shall first consider the simple action of the armature unmodified by reactions, and then see how this condition is altered.

Simple Action. Fig. 30 represents an eight-coil ring armature of a bipolar machine. Coils *C* and *G* are moving directly across the strongest part of the magnetic field, and are therefore generating the maximum E. M. F. Coils *B* and *F* are just entering the field, and *D* and *H* are leaving the field and generating less E. M. F. than *C* and *G*.

Coils *A* and *E* are not cutting across the field, and therefore generating no E. M. F. Now all coils on the right-hand half of the ring are generating an E. M. F. in the same direction, and therefore assist each other to give the total E. M. F. of the machine, while all coils on the left-hand half are also assisting each other, but generating an E. M. F. in the opposite direction to that of the right-hand half. The current induced in the outside wires at the right-hand side approaches the observer, while the current in the outside wires at the left recedes from the observer, causing an ascending current in each half of the ring from the lower brush to the upper brush. It will be noted that each brush for the position shown, bears upon two commutator bars, and the upper brush takes the current directly from coils *B* and *H*, while the lower brush conducts the current directly to coils *D* and *F*. The thickness of brushes is always sufficient to bridge the insulation between commutator bars. Coils *A* and *E* are therefore momentarily short circuited or cut out of the armature circuit, and as each coil takes these positions, each is successively short circuited. The current which the coil formerly carried then seeks the direct path through the commutator bar to the brush. After being short circuited and carrying no current, the coil is then grouped with the other half of the ring, and a current is set up in the opposite direction through the coil. Hence as each coil passes from one half of the ring to the other, the current through it in one direction is interrupted, which renders the coil temporarily inactive, and as it passes to the other side of the ring, a current is set up in the opposite direction. In this manner the commutation of currents takes place.

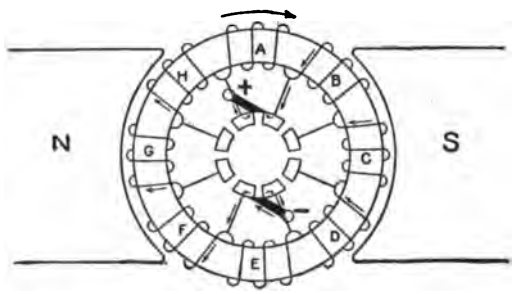


Fig. 30.

A plane through the inactive position of the coils is called the *neutral* plane, and coils *A* and *E* are said to be in the neutral positions.

Magnetic Field Due to Field Winding. The magnetic field, created by the field coils alone, and unaltered by armature reactions, is represented by Fig. 31. The small circles represent the cross section of each wire, of which only a few are shown, and the direction of current in the field coils is indicated by the dots

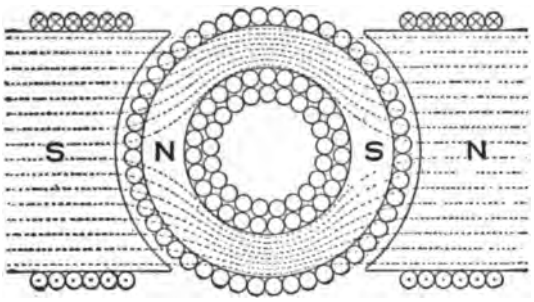


Fig. 31.

and crosses within the circles. In those wires having crosses, the current is flowing from the observer, the cross indicating the tail of a retreating arrow, and in those wires having dots the current is flowing towards the observer, the dot indicating the point of an advancing arrow. The field, created by a current in the field coils only, is uniform and passes through the armature core as shown.

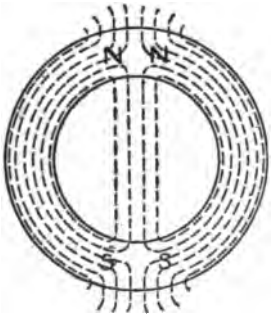


Fig. 32.

Magnetic Field Due to Armature Winding. When a generator is supplying current, the armature is magnetized by its own current, and the magnetic field in the armature due to its current alone is represented by Fig. 32. The current in each half of the ring magnetizes its half independently of the other, and for the arrangement shown in Fig. 30 each produces a north pole at the lower portion of the ring and a south pole at the top. The two like poles thus created adjacent to each other have a repellant effect and create what is termed a *consequent* pole, causing the magnetic lines to leave the ring at these points, part of the lines passing directly across the ring and part

passing outside the ring in curved lines from the lower portion to the top.

When a ring thus magnetized is between the field poles, the poles will serve as a path for many of the lines, and a field such as represented by Fig. 33 results.

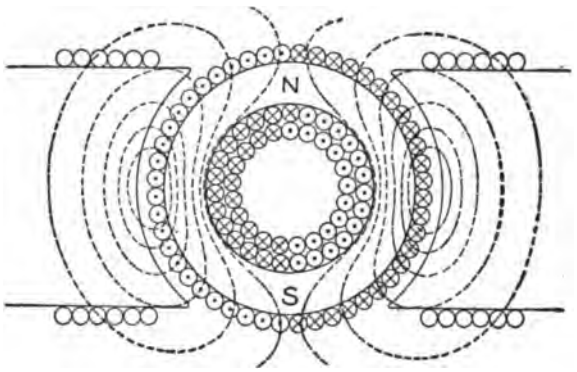


Fig. 33.

Resultant Field. When a machine is in operation, the magnetism due to both the field and armature windings is present, and the field obtained will therefore be the resultant of the two fields represented by Figs. 31 and 33. These fields, when united,

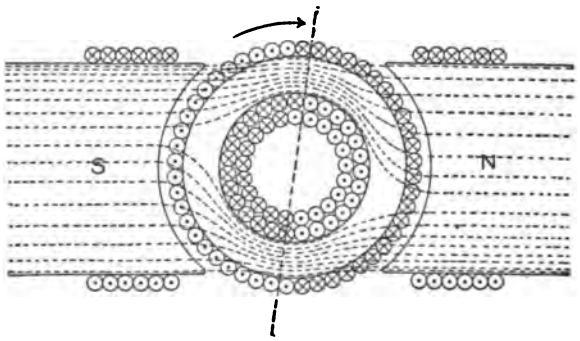


Fig. 34.

will give a resultant field, as represented by Fig. 34. The field due to the field windings being the stronger, will still maintain the same general course, but the effect of the armature is to produce a resultant field in an oblique direction. It also causes a

crowding of the magnetic lines at the tips of the poles where the conductors pass from under the same, and a weakening of the lines at the tips which the conductors are approaching. It thus appears that the neutral plane is turned somewhat in the direction of rotation as indicated by the dotted line. After passing from under pole pieces, the conductors generate but little E. M. F., and when they are in the neutral plane they generate none whatever; therefore from the above it appears that the brushes should be set in such a position that coils will be short circuited when in the neutral plane. Hence the brushes, instead of being placed midway between the poles in a ring-round machine will be

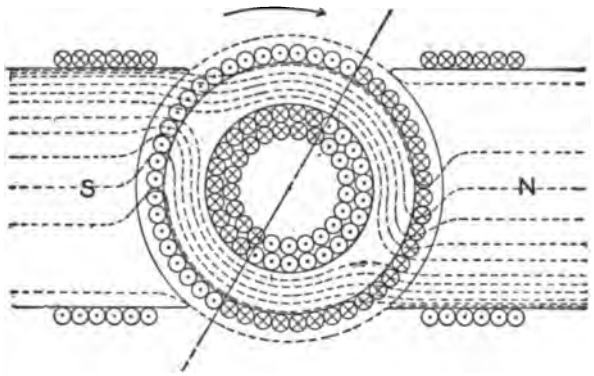


Fig. 35.

shifted slightly in the direction of rotation of the armature. The amount which the brushes are shifted from their mid-position is called the *lead* or *angle of lead.*

This shifting of the brushes causes a still further distortion of the resultant field, as the field due to the armature winding alone, instead of being vertical as represented in Figs. 32 and 33, will be inclined, and coincide with the neutral plane. This inclination aggravates the distortion, causing the neutral plane to be shifted to a greater degree than represented by Fig. 34. The actual result obtained will therefore be better represented by Fig. 35, all conductors on one side of the neutral plane carrying currents in an opposite direction to those on the other side.

There is another cause for additional shifting of the brushes which causes a slightly greater distortion. This is due to self-induc-

tion of the armature coils. From the preceding pages it appears that each coil is short-circuited as it passes by the brushes; the current which the coil carried as it approached a brush ceases to flow, and as it passes to the other side, a current in the opposite direction is set up. On account of self-induction, however, the current which the coil formerly carried tends to continue, and the current in the opposite direction is choked back for a slight interval of time, as self-induction tends to oppose a decrease or increase of current strength. In order to counteract this effect, the brushes are shifted a slight amount in the direction of rotation, so that when each coil is short-circuited it is at that time already somewhat effective in cutting lines of force, so that a slight E. M. F. is generated which hastens the time of decrease in current in one direction, and assists the increase of current in the opposite direction.

We may sum up the effect of armature reaction as follows:

1. The magnetic field due to the armature windings is at right angles to that of the field windings, giving a resultant distorted field.

2. On account of this distortion, and in order to prevent sparking, the brushes must be shifted in the direction of rotation of the armature, and this new position of the brushes in itself produces a still greater distortion.

3. The further shifting of the brushes to overcome the effects of self-induction causes additional distortion.

Shifting of Brushes with Variable Load. When the armature supplies no current and therefore has no load, the field is substantially uniform, as no distortion due to the armature exists. The brushes may therefore be set at the mid-position between the poles. When the load is light, the small armature current causes but little distortion, and therefore the brushes need only a slight lead to secure sparkless running. As the load increases and the armature current becomes greater, the distortion is correspondingly increased, and consequently the proper position for the brushes changes with the load. Hence in the operation of generators, a variation in load will cause sparking at the brushes unless they are shifted to the proper positions. Many machines are now so well designed that but little shifting is necessary from no load to

full load, and in some machines the necessity is entirely overcome by special compensating arrangements. Of course, if the field due to the field windings is made very powerful compared with that due to the armature, the distortion will be proportionately less, and in many machines now made, where this plan is carried out, there is little or no need of shifting the brushes with change in load.

Distortion Due to Drum-Wound Armatures. In the above discussion of armature reactions we have referred to distortion due to ring-wound machines only. The same effect in a lesser degree takes place with drum-wound armatures.

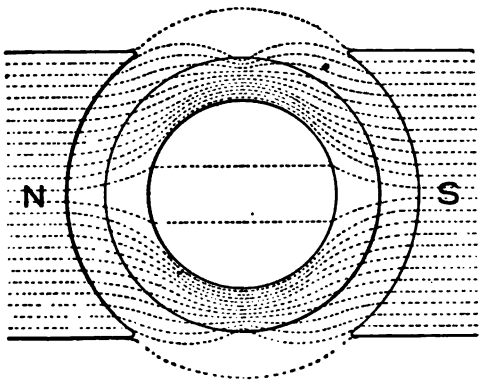


Fig. 36.

Magnetic Leakage. If the magnetic circuit is well designed and made of ample cross-section, practically all the lines of force will pass through the armature core from pole to pole. All lines which do not pass through the core are of course useless, and the E. M. F. generated is less in a corresponding degree. Fig. 36 illustrates the manner in which lines may pass from pole to pole without being of any service. This is called magnetic leakage.

LOSSES IN THE GENERATOR.

There is always some loss in converting the mechanical energy necessary to drive a generator into electrical energy. That is, if 15 horse-power is necessary to drive a certain machine, the equivalent electrical energy derived from the same is always somewhat less. For example, the electrical equivalent of 15 horse-power is $15 \times 746 = 11{,}190$ watts, but instead of having this amount available at the dynamo terminals, there may be perhaps 90 per cent of this value, or 10,071 watts.

We shall now consider separately the various losses, all of which are dissipated in the form of heat.

These may be classified in two groups, known as the *electrical* losses and the *stray power* losses, and are as follows:

Electrical losses.

(*a*) Armature conductor $I^2 R$ loss.

(*b*) Field wire $I^2 R$ loss.

Stray power losses.

(*c*) Friction of bearings.
(*d*) Friction of brushes.
(*e*) Friction due to air resistance.
(*f*) Waste currents in coils during commutation.
(*g*) Hysteresis in armature core.
(*h*) Eddy or Foucault currents in armature core.
(*i*) Eddy or Foucault currents in pole pieces.
(*j*) Eddy or Foucault currents in armature conductors.

Of these the electrical losses vary with the load put upon the machine, whereas the stray power losses remain practically constant for all loads. As the stray power losses are always present to the same degree whatever the load may be, it is desirable that they should be as low as possible, since on light loads they may be a considerable proportion of the total power.

Electrical Losses. The electrical losses are those due merely to the resistance of conductors through which a current flows, and may be computed by taking the square of the current passing multiplied by the resistance, or $I^2 R$; where I is the current and R the resistance of the circuit. All circuits carrying a current, whether windings of a generator or mains which distribute power, are subject to this loss of energy. Hence if the resistance and current are known, the power lost may be readily obtained.

For example, if the resistance of a circuit is 80 ohms and the current 40 amperes, the power lost will be $40^2 \times 80 = 128{,}000$ watts, or 128 K. W. The power lost may also be computed if the current and E. M. F. applied to the circuit are known, by taking the product of the two quantities. This is evident, as from Ohm's law $I = \frac{E}{R}$, and substituting this quantity for one I in $I^2 R$, we have $I \times \frac{E}{R} \times R = IE$, where E is the E. M. F., applied to the circuit. In the above problem the E. M. F. applied to the circuit is, by Ohm's law, $E = RI = 80 \times 40 = 3{,}200$ volts, and

the loss in watts is, therefore, 40 × 3,200 = 128,000 watts = 128 K. W., the same as above.

The data for computing the loss in the field windings of a machine can be easily obtained. It is merely necessary to measure the resistance of the windings and the current in the same, or to measure the current and the voltage applied to the terminals of the field windings. The resistance of shunt windings will always be high and the current small, while the resistance of series windings will always be low and the current large.

The data for calculating the loss in the armature is obtained with more difficulty. As the armature is itself generating an E. M. F., the fall of potential in the armature due to its resistance or the *drop* in the armature cannot be measured, and we are therefore compelled to compute the loss from resistance measurements and must use the formula $I^2 R$. The current can be easily measured, but there is some difficulty in measuring the resistance accurately. In this resistance, the armature winding, commutator, brushes and resistance of contacts between commutator and brushes are included. The total resistance is very small, and therefore a slight error in its measurement will make a considerable percentage difference. Also the resistance must be measured when the armature is not rotating, and the measurement obtained may be somewhat different from the resistance when the machine is in operation.

As the resistance of the conductors is greater when hot than when cold, the resistance measurements for calculating the loss in the armature as well as in the fields must be made after the machine has been in operation at full load for a few hours, when all parts will be thoroughly warmed up.

Example.— The resistance when hot of the shunt winding of a certain 120-volt 200-ampere shunt machine is 98 ohms. The resistance of the armature when hot is .019 ohm. What are the electrical losses at full load?

Solution.— The voltage of the machine which is applied to the shunt terminals is 120 volts, and by Ohm's law the current in the shunt windings is

$$I = \frac{E}{R} = \frac{120}{98} = 1.22 \text{ amperes.}$$

The loss in the field winding is therefore $I^2 R = 1.22^2 \times 98 = 146$ watts approximately.

Both the main current and the shunt current pass through the armature; hence the armature current is 201.22 amperes, and the resistance is .019 ohm; the loss is therefore $(201.22)^2 \times .019 = 769+$ watts.

The electrical losses are consequently $146 + 769+ = 915$ watts.

Ans. 915 watts.

Example.— A 500-volt compound-wound generator is designed to supply 650 amperes. The armature resistance is .009 ohm. The current in the shunt winding is 3 amperes, and the resistance of the series winding is .0011 ohm. Find the total electrical loss of the machine.

Solution.— As the current in the shunt field winding is 3 amperes, and the voltage applied to the terminals is 500, the loss in watts is given directly by their product, or $3 \times 500 = 1{,}500$ watts.

As the main current of the machine passes through the series winding, the resistance of which is .0011 ohm, the loss therein is $650^2 \times .0011 = 4{,}647.5$ watts. Likewise the loss in the armature is $653^2 \times .009 = 3{,}837.6$ watts.

The total loss due to resistance therefore equals $1{,}500 + 4{,}647.5 + 3{,}837.6 = 9{,}985$ watts.

Ans. 9,985 watts.

Example.— A 220-volt compound dynamo delivers 300 amperes. The armature resistance is .014 ohm, the shunt winding takes 2.18 amperes, and the fall of potential in the series coil is .54 volt. What are the electrical losses?

Solution.— The loss in the shunt field is $220 \times 2.18 = 479.6$ watts. The current passing through the armature is $300 + 2.18 = 302.18$ amperes, and the armature loss is therefore

$$(302.18)^2 \times .014 = 1{,}278.4+ \text{ watts.}$$

The loss in the series coil is the product of the lost voltage (i.e., the drop) in it and the current; that is, $.54 \times 300 = 162$ watts. Hence the total electrical losses are $479.6 + 1{,}278.4 + 162 = 1{,}920$ watts.

Ans. 1,920 watts.

Friction Losses. The friction losses include those due to mechanical friction of the bearings and of the brushes upon the commutator and also the friction caused by the resistance of the air acting on the rotating armature.

The friction of the bearings varies with the type of machine, whether belt driven or direct connected to the engine, type of bearing, lubrication, etc.

The loss due to bearing friction was formerly considerable, but the bearings of modern dynamo-electric machines have been designed and constructed with great care with the result that friction from this source has been reduced to a minimum. The bearings are usually made self-oiling by means of metal rings which rest upon the shaft and dip into oil which is contained in a reservoir in the bearing. As the shaft revolves, the rings carry the oil up to the shaft. In this manner almost perfect lubrication is secured. In some cases ball bearings have been used with good results; they reduce friction and lessen the cost of lubrication. Ball bearings are not extensively used on account of some mechanical difficulties which have not yet been entirely overcome.

The brush friction is subject to great variation. It is important that the brushes bear upon the commutator with sufficient pressure to insure good electrical contact. Brush holders are usually arranged so that the pressure of the brushes may be varied to obtain the best results. Although brush friction may sometimes be considerable, it usually amounts to a very small percentage of the total loss.

The resistance of the air upon the armature is usually insignificant except when the armature is arranged to act as a fan for the purpose of ventilation, and even then the loss from this source is so slight that it need hardly be considered.

Hysteresis Loss. As an armature rotates, the magnetization of its core is constantly changing at every point. The magnetic lines in passing through the armature from pole to pole cause varying degrees of magnetization in its different parts, and the rotation of the armature brings every part of it successively through these changes. Hence that part of the armature in the neutral plane is magnetized to the highest degree with lines passing through it in one direction; when opposite a pole, the

magnetization is a minimum, and when in the next neutral plane it is again magnetized to the highest degree but with lines passing in the opposite direction. All parts of the armature core are therefore being constantly magnetized in one direction, then demagnetized and magnetized in the opposite direction, again demagnetized, and so on as each pole is passed. This gives rise to what is called hysteresis loss, which will now be considered.

When a piece of iron is subjected to an increasing and decreasing magnetizing force, the magnetization for equal magnetizing forces will not be the same, and it is found that the magnetism lags behind the magnetizing force, or in other words, the metal has a tendency to maintain any magnetic state which it has once acquired. This property of iron is called *hysteresis*, from a Greek word meaning "to lag behind."

Fig. 37 shows the hysteresis curve of a piece of wrought iron, or the resultant magnetization when the magnetizing force is varied. The abscissæ represent the magnetizing force in ampere-turns per centimeter of length, and the ordinates indicate the resultant magnetization in lines per square centimeter. Abscissæ to the right of the zero point represent positive values and those to the left negative, while ordinates above the zero point are positive and those below are negative. The curve which begins at *A* shows that the iron had some residual magnetism before any magnetizing force was applied. As the magnetizing force is increased positively, the magnetic induction gradually increases as in Fig. 37, until point *B* of the curve is reached. Then the magnetizing force is gradually withdrawn, but the magnetic induction does not fall as fast as it previously rose, for when the magnetizing force is reduced to 10, the induction is nearly 14,000 lines instead of 12,800, as it was on the ascending curve. When the magnetizing force is reduced to zero, the induction is still high, as represented by point *C* of the curve. Increasing the magnetizing force still further in a negative direction gives an induction curve to point *E*.

A gradual decrease of the magnetizing force to zero and an increase in a positive direction to a maximum gives the curve through points *E F G H*. It may be noted that point *H* does not coincide with point *B*, although the magnetizing force is increased

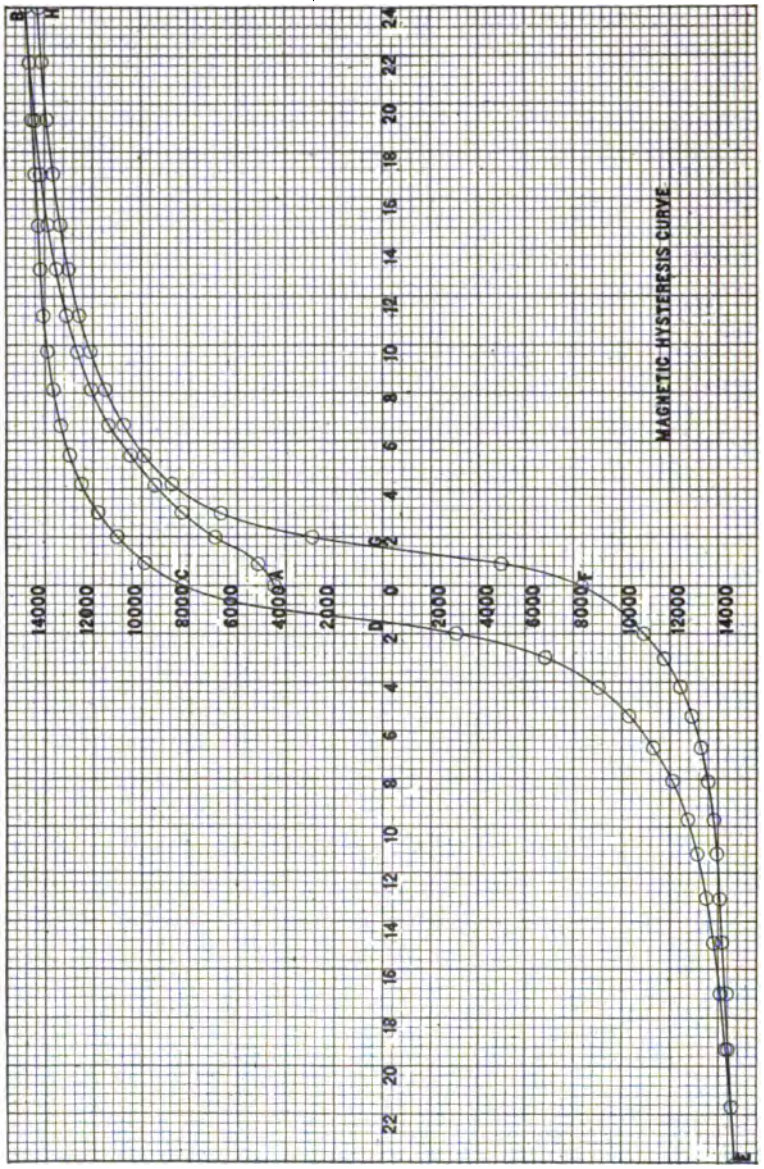

MAGNETIC HYSTERESIS CURVE
B
H
A
C
D
E
F
14000
12000
10000
8000
6000
4000
2000
0
2000
4000
6000
8000
10000
12000
14000
2
4
6
8
10
12
14
16
18
20
22
24

Fig. 87.

VIEW OF ELEVATED ELECTRIC RAILWAY, BOSTON
(By Courtesy of the Sprague Electric Company)

from zero to a maximum for both curves. However, in the first magnetization from *A* to *B* the induction had a considerable positive value at the beginning, whereas in the curve *F G H* it had a large negative value which had to be overcome. If the magnetizing force were now decreased, reversed, increased, etc., a second curve similar to *B C D E F G H* would be obtained. Such cycles of magnetism as described above always give curves with an enclosed area.

This series of changes is what takes place in the core of an armature, and it is evident that the resultant magnetism always lags behind the magnetizing force as if there were a certain molecular friction of the iron which had to be overcome.

There is, therefore, a certain loss of energy due to hysteresis which is dissipated in the form of heat. The amount of this energy is proportional to the area enclosed by the curve, and it is therefore an easy matter to judge of the comparative magnetic qualities of two samples of iron by plotting the hysteresis curve of each.

The harder the iron, the greater the hysteresis loss. This loss varies as the 1.6 power of the magnetic induction and is also proportional to the rate at which the reversals of magnetism take place, and of course, the greater the amount of metal in which the reversals occur, the greater the total hysteresis loss.

The heating which occurs in the core of an armature due to hysteresis should not be confused with the additional heating due to eddy or Foucault currents. Hysteresis causes heating even if the core is carefully laminated.

Fig. 38 shows two hysteresis curves drawn one over the other, one of which is from a sample of wrought iron and the other from a sample of steel.

The curve enclosing the smaller area is for wrought iron, and the larger for steel. Since the area enclosed by the hysteresis curve is the measure of energy dissipated in heat due to hysteresis, it is evident that the hysteresis loss for wrought iron is much less than for steel. Wrought iron would, therefore, be better adapted for use in armature cores.

The loss due to hysteresis cannot be accurately determined. For very soft iron where the hysteresis curve encloses a small

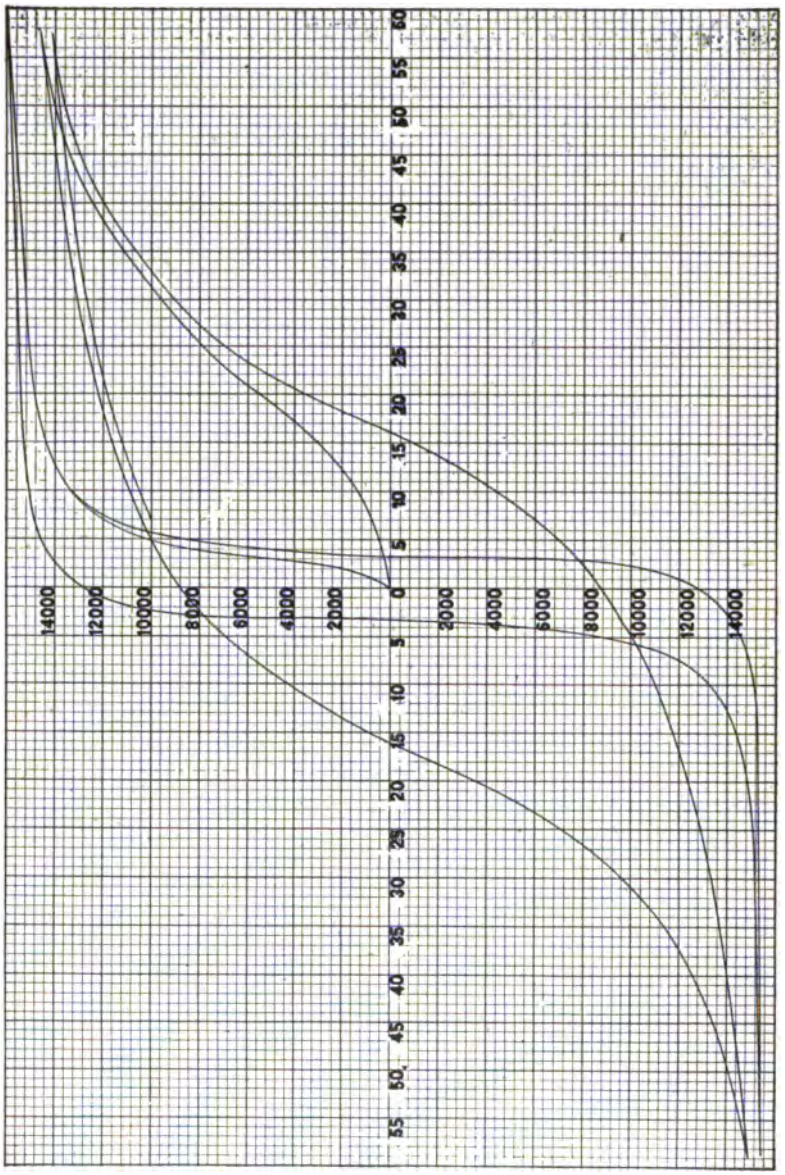

14000
12000
10000
8000
6000
4000
2000
0
2000
4000
6000
8000
10000
12000
14000
5
10
15
20
25
30
35
40
45
50
55
60

Fig. 38.

area the loss of energy during a complete reversal of magnetism is slight; with hard iron the amount of energy wasted per cycle is somewhat greater, but in practice the loss from this source is usually small. In order that this loss may be as small as possible the softest wrought iron or steel should be selected for armature cores.

Eddy Current Loss. We know that whenever conductors are moved in a magnetic field in such a manner as to cut across the lines, or when the field about the same is varied, an E. M. F. is induced which will cause a current to flow if a closed circuit exists. This principle applies to large metallic masses as well as to the conductors, and therefore currents may be set up in a generator where they are useless, thus causing undesirable heating of parts and loss of energy. Such currents are called eddy or Foucault currents.

The armature core, if made of one solid mass, is subject to these wasteful currents to an excessive degree, since it consists of a conducting mass revolving in a magnetic field. It is evident that the outer surface of the armature core cuts across the magnetic field the same as the conductors upon it, and an E. M. F. is therefore induced in the iron itself, tending to set up currents near its surface. The direction of these currents will be at right angles to the lines of force or the induced current in the exterior of the armature core will be parallel to the current in the armature conductors. The interior portion of the core serves to complete the circuit for these currents, and therefore innumerable currents, due to this cause, will exist in the core itself. The E. M. F. induced may be slight, but the resistance of the core is so small that the resultant currents may be large. These currents are always strongest near the exterior surface of the armature core. This eddy current loss described above varies as the square of the speed and also as the square of the magnetic induction.

Lamination. The value of such currents can be decreased by reducing their E. M. F. or by increasing the resistance which is offered to their flow. These results can be accomplished by constructing the armature core of thin sheets of iron carefully insulated from each other. These thin sheets or discs are placed perpendicular to the axis of the armature, thus being perpendicular

to the direction of induced currents, but parallel with the lines of force passing through the core. Consequently they do not interfere with the passage of magnetism from pole to pole, nor increase the magnetic resistance of the armature. They do, however, effectually interrupt and reduce the eddy currents because such currents can then exist only within each separate disc, as shown in Fig. 39, and if the discs are made sufficiently thin and the insulation between them is good, the loss due to wasteful currents is slight. An armature built up of discs or thin sheets of iron is said to be laminated. The thickness of the discs should not exceed two millimeters, and they should be insulated by varnished paper, enamel, or by being slightly oxidized on the surface.

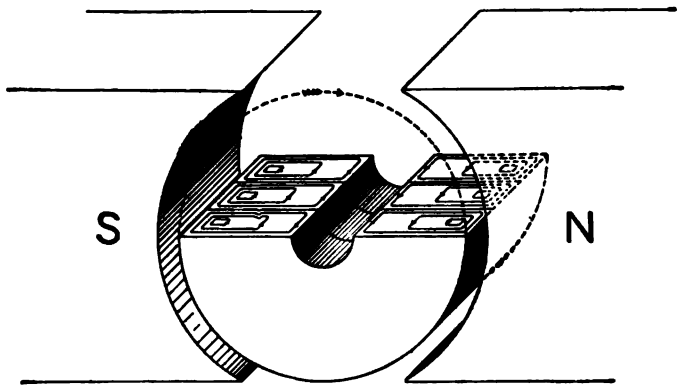
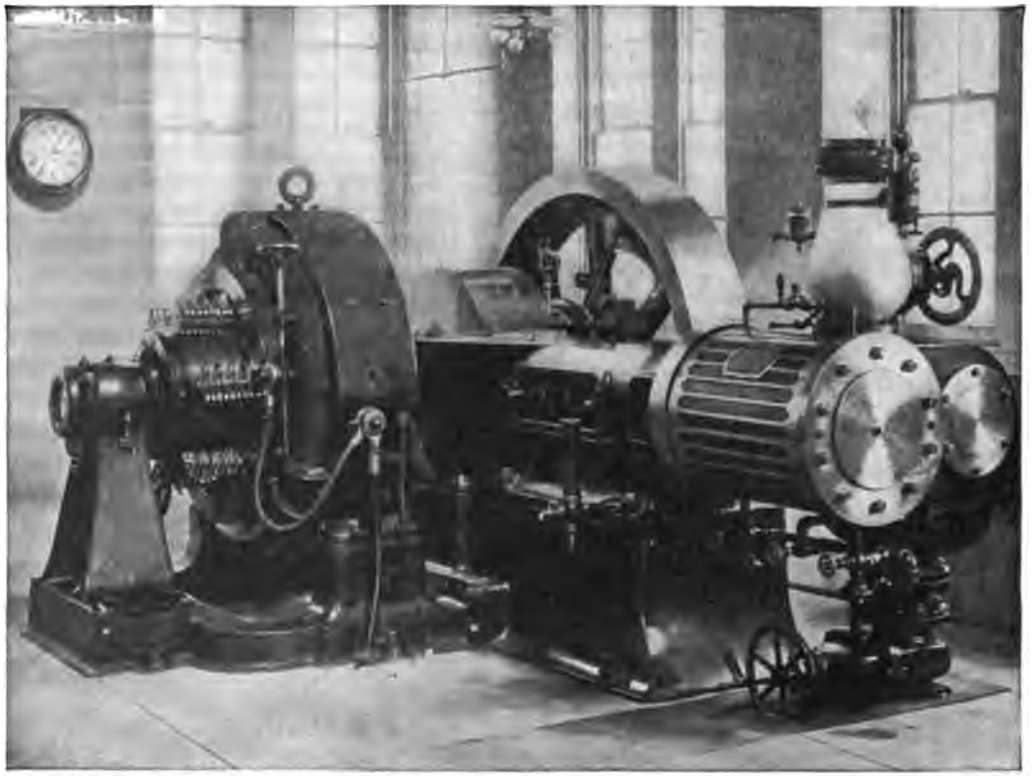


Fig. 39.

Eddy Currents in Pole Pieces and Armature Conductors. Polar tips in which magnetization varies become heated. Hence tips are now laminated, the laminations being parallel to the lines of force but perpendicular to the direction in which currents would be induced. Armature conductors are also subdivided for the same reason, and the loss in eddy currents is reduced to a total of usually less than one-half of 1%.



C & C Lighting and Power Plant, Kirschbaum Building, Philadelphia. One 60 K. W. Generator.

SECTION 4.

DIRECT CURRENT DYNAMOS.

Having become familiar with some of the fundamental principles and laws governing the operation of a dynamo by a study of electro-magnetic induction, one is prepared for a more detailed study of the machine. The three important types of dynamos, the series, the shunt and the compound, have already been briefly explained, but will now be considered more in detail, and their properties will be more fully explained and illustrated by diagrams.

All of the important parts of the dynamo, such as the armature, the commutator, the brushes and brush-holders, and the field will now be treated separately and in detail.

In general, dynamos are used to furnish either light, heat or power. A dynamo receives at the pulley a certain amount of mechanical energy, which it transforms into electrical energy and delivers through the circuits with which it is connected. The power in a circuit is equal to the product of the difference of potential, E, between the terminals of the dynamo and the current, I, flowing in the circuit, or $E\,I$. When this product, $E\,I$, is great, a large amount of work is expended in the circuit, and to express this fact it is said that a heavy load has been put upon the dynamo. The value of $E\,I$ is increased by increasing either E or I, or both; that is, the load on the dynamo is increased when a larger current comes from it, or when the same current flows, but at a higher voltage.

We have seen that electrical power is measured in units, to which the name **watt** is given, a watt being the power of 1 ampere under a pressure of 1 volt; the product of the number of amperes and the voltage of a circuit is therefore its power. A dynamo which maintains a difference of potential between its terminals of 10 volts, and which delivers through the circuit connected with its terminals 5 amperes of current, is furnishing

energy at the rate of 50 watts. Had this same dynamo been working at a difference of potential or pressure of 25 volts, and had it been delivering only 2 amperes in the circuit, it would have still been working at the rate of 50 watts. It makes no difference in the amount of power what the pressure or the current is, as long as they are of such magnitudes that their product remains the same; the dynamo will then furnish the same amount of energy per unit of time, and consequently it will take the same pull on the belt, and the same effort in the engine to drive it.

These considerations suggest two methods for distributing power and light. The necessary condition of supply is that the dynamo must be ready to meet a demand which varies between certain limits. This may be done by causing the dynamo to keep the voltage at its terminals constant at all times, and to vary the current according to the demand; or the dynamo may keep the current supplied constant, and vary the voltage at its terminals according to the demand for energy. It will make no difference to the driving power which is done. It has, however, for many reasons, been found most convenient to supply incandescent lighting systems by the first method, and arc lighting systems by the second. Power distribution has occasionally been accomplished by the second method, but the first is generally used.

In the study of **Direct Current Dynamos** it will therefore be of advantage to divide the subject into two parts: (1) Constant Potential Dynamos, machines that supply current at a constant pressure for all loads; and (2) Constant Current Dynamos, machines that supply a current of constant strength for all loads.

By having more lamps or running more motors on the circuit we increase EI, or the load upon the dynamo. In constant potential machines, E remains constant for any change in the number of lamps or motors on the circuit, within the limits of the capacity of the machine; hence, to increase the load on the dynamo, I must be increased, and it is seen readily enough that the load is proportional to I if E remains constant, or since I is inversely proportional to R, the resistance of the circuit, the load on a constant potential machine is inversely proportional to the resistance of the circuit.

In a constant current machine I is constant and E must be

increased if E I, the load, is to increase. If E rises, and I remains the same, then R must increase according to Ohm's law. Hence the load on a constant current machine is proportional to E and to R. An increased load on constant current machines requires larger values of E and R; on constant potential machines it requires a larger value of I and a smaller value of R.

If E is to remain constant, the magnetization produced by the field coils must remain constant, or, in other words, the conductors on the armature must cut the same number of magnetic lines of force each second. If I is to remain constant and E is to increase, then a correspondingly greater number of lines of force must be cut each second.

The essential difference between the two types of machines then is that in one there is a nearly constant magnetic flux for all loads, and in the other there is a magnetic flux varying with the load. The two types of constant potential and constant current dynamos will be considered separately.

Characteristic Curves. A characteristic curve, as its name indicates, is one which shows the characteristics or peculiarities of the dynamo to which it belongs. Such a curve is obtained by plotting the corresponding values of volts and amperes of the dynamo at different loads. The data for such a curve are obtained by taking simultaneous readings of current and voltage at various loads while the dynamo is in operation. Upon a piece of cross-section paper the amperes are plotted as abscissæ and the volts as ordinates; that is, the number of amperes of one reading are laid off horizontally from the lower left-hand corner, called the origin, covering as many divisions as there are amperes; and from this point a distance is laid off vertically, covering as many divisions as there are volts corresponding to that number of amperes. The point thus obtained is a point on the curve. The remaining readings are laid off in like manner, obtaining a number of points; a smooth curve through these points gives the desired characteristic.

A number of very important properties of a dynamo may be shown by means of the **characteristic curves.** These same characteristics may generally be figured out mathematically, but it is more correct and more satisfactory to get at the results from a practical test of the finished machine, as a general

rule. These characteristic curves explain the actions and possibilities of a dynamo in very much the same way that the indicator card of a steam engine gives its desired information. By drawing the characteristic curves to some known scale, the horse-power at which the dynamo will work with the greatest efficiency can be calculated.

Having drawn the characteristic curve of a machine to some particular scale, and knowing either the current, I, or voltage, E, at which the dynamo is working, the other value may be read off the curve directly. The value of the current, multiplied by the corresponding voltage, gives the output of the machine in watts, and this divided by 746, the number of watts corresponding to 1 horse-power, gives the output of the machine in horse-power.

It is possible to plot horse-power curves on the same paper with the characteristic curve (see Fig. 8), since horse-power $= \frac{\text{volts} \times \text{amperes}}{746}$. Any combination of amperes $\times$ volts which will give 746 is equal to 1 horse-power; thus 74.6 amp. $\times$ 10 volts $=$ 1 horse-power. Evidently, then, there is an infinite number of points the product of whose co-ordinates equals 746, and a line drawn through these points is a curve of 1 horse-power. If the characteristic of the dynamo cuts the curve at any point, it means that at that point the dynamo is furnishing 1 horse-power of electrical energy. It follows at once that curves may be similarly drawn for 2, 3, 4, or any number of horse-power. Then a glance at the characteristic curve will reveal at once what the activity of the dynamo is.

THE SERIES DYNAMO.

After the invention of the magneto machine with its permanent steel magnet, it was not a very great step to put coils of wire on the field magnets, and cause the current, as it comes from the armature, to pass through them before being led to the outside circuit, thus obtaining self-excitation (see Fig. 1).

A machine so connected is called a **series dynamo** because all its conducting parts are in series with one another. The properties

of this machine can be best explained by considering its characteristic curve. Every individual machine will of course have a curve differing somewhat from those of other machines which are differently proportioned, but the same general features will be present in the curve of all series dynamos. There are three characteristic curves possible for every dynamo, the **external,** the **internal** and the **total.** The distinction is as follows: the electromotive force generated by the machine is used up in two ways; in forcing the current through the resistance of the outside circuit, and in forcing it through the internal resistances of the dynamo itself. Therefore the voltage measured by a voltmeter applied to the terminals of the dynamo is the voltage which is forcing the cur-

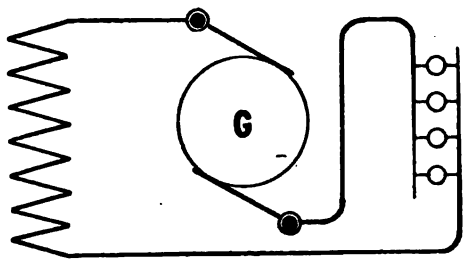


Fig. 1. Diagram of Series-Wound Dynamo.

rent through the outside circuit. This voltage is given by the lower curve in Fig. 2, which is called the **external characteristic.** To get the total electromotive force generated by the machine it is necessary to multiply the current by the armature resistance and add the result to the voltage measured at the terminals. The upper curve in Fig. 2 gives the total E. M. F. and is called the total characteristic. A characteristic curve is external, internal, or total according as the volts plotted against the amperes are the volts measured at the terminals, the volts lost in the armature, or the total volts. From the series characteristic curve shown in Fig. 2 it is evident that when the circuit is open and there is no current, there is no voltage generated by the machine. With the current equal to zero, the strength of the field due to the field magnets is zero. Were there any permanent magnetism remaining in the iron as there generally is, there would be a slight electromotive force generated, and the curve would

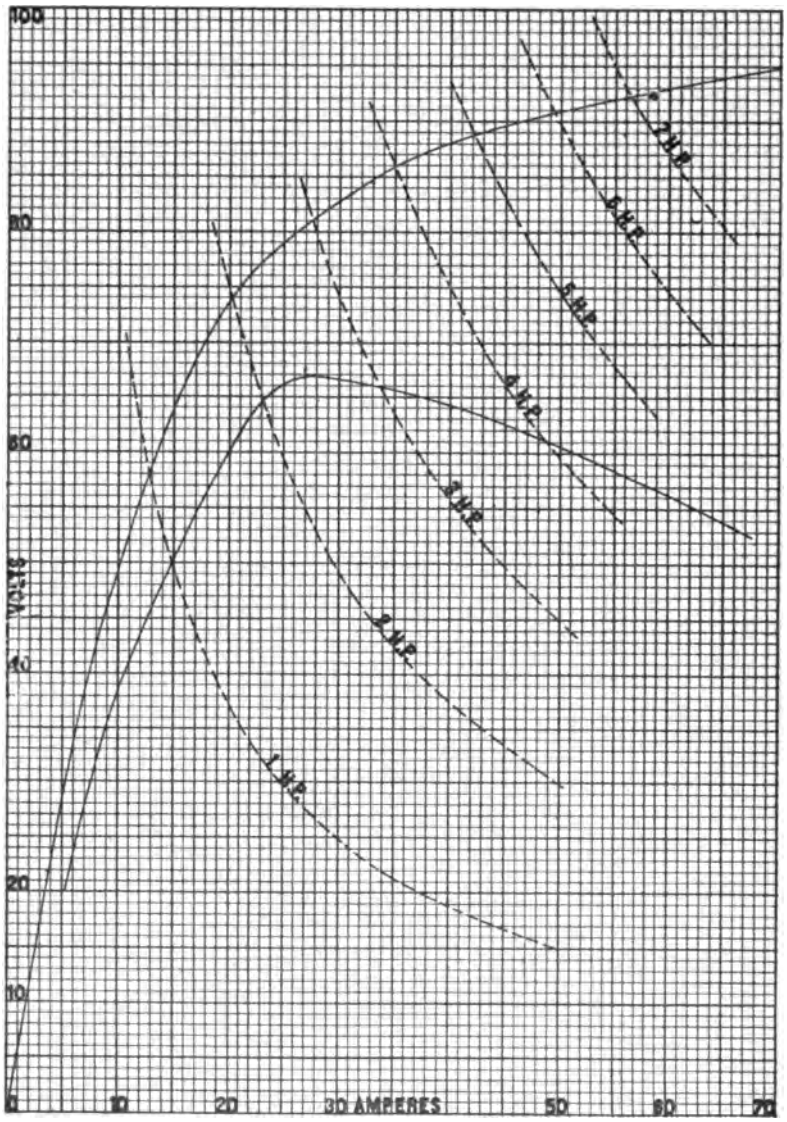


Fig. 2. External and Total Characteristic Curves of Series Dynamos.

Motor Generator Sets, consisting of a Single-Phase Self-Starting A. C. Wagner Motor and a Direct-Current Generator for Charging Batteries for Automobiles, Telephone Exchanges, etc.

not start at zero but a little way up on the scale. A dynamo with no magnetism whatever could not be made to take a load, or *build itself up* as the action is called. The curve runs up very steeply and approximately in a straight line, since the field, and consequently the electromotive force, increases with the increase in the current. This action goes on until the iron approaches saturation, or the point where it cannot take up any more magnetism. As it nears this point the curve bends over more and more, though still rising, until the actual point of saturation is reached. Beyond this point any increase in current cannot increase the strength of the field much and another factor becomes of importance, namely, the armature reaction. The increase in current must of course increase the armature field which tends to weaken the field due to the field magnets and consequently the voltage of the machine. It should be understood that the field of the armature does not actually exist because it is overpowered by the field magnets; it would exist were the field magnets absent and the current maintained by some external means. Its effect is to distort and weaken the field due to the field magnets. Beyond the saturation point therefore, any increase in current cuts down the field and consequently the electromotive force generated in the armature, provided the speed remains the same.

There is a very interesting property of series dynamos, which is best explained in connection with the characteristic curve. There is for every series dynamo a certain value of the current called the *critical current* at which the machine is unstable. Any increase in the circuit resistance tending to decrease the current below this value will result in the complete *unbuilding* of the machine and the consequent loss of load. Similarly the machine will not take a load or *build up* unless the resistance of the circuit is low enough so that the current can reach the critical value.

An examination of the characteristic curve shows that at a point a little more than two thirds of the way up to the maximum value of the curve, any decrease in the current of the machine decreases the voltage much more rapidly than is the case at any point higher up. This large decrease in voltage still further decreases the current, which result reacts on the voltage again, and this process goes on until the machine is completely unbuilt,

Total and external characteristic curves of a small Wood arc light dynamo are shown in Fig. 8. The total voltage generated by the armature is equal to the voltage observed at the terminals plus the lost voltage of the armature and series coils.

This was calculated by the equation

$$E' = E + I(r_a + r_{se})$$

where r_a was 5.4 ohms and r_{se} was 6.83 ohms.

The observed voltages are corrected for a speed of 1150 revolutions.

The electrical efficiency for this machine was calculated and found as follows:

DATA FOR EFFICIENCY OF SMALL WOOD DYNAMO.

Speed	I	$E' I'$	$E I$	$\frac{E I}{E' I'}$
1150	1	288	88	31%
1150	4.4	1727	1408	81%
1150	4.6	1840	1509	82%
1150	6.0	2704	2280	84%
1150	7.0	3389	2884	85%

The usual use of the constant current dynamo is for arc lighting. Arc lamps are commonly run in series and require about 10 amperes, and a potential of about 50 volts across the terminals of each. To maintain a constant current in the circuit the E. M. F. at the brushes of the generator must then increase 50 volts as each lamp is thrown in.

Constant current dynamos are series wound. Of such machines, we know that with a variable resistance in the external circuit, the current, or E. M. F. or both will vary. In the case of a machine supplying a certain current, if the resistance is increased the current strength will fall, and the field coils being in series the magnetic field is weakened, thereby lowering the E. M. F. and still further lessening the current. On the other hand if the external resistance is reduced, a larger current flows and a correspondingly higher potential is generated. Obviously, if such a machine is required to give a constant current through a

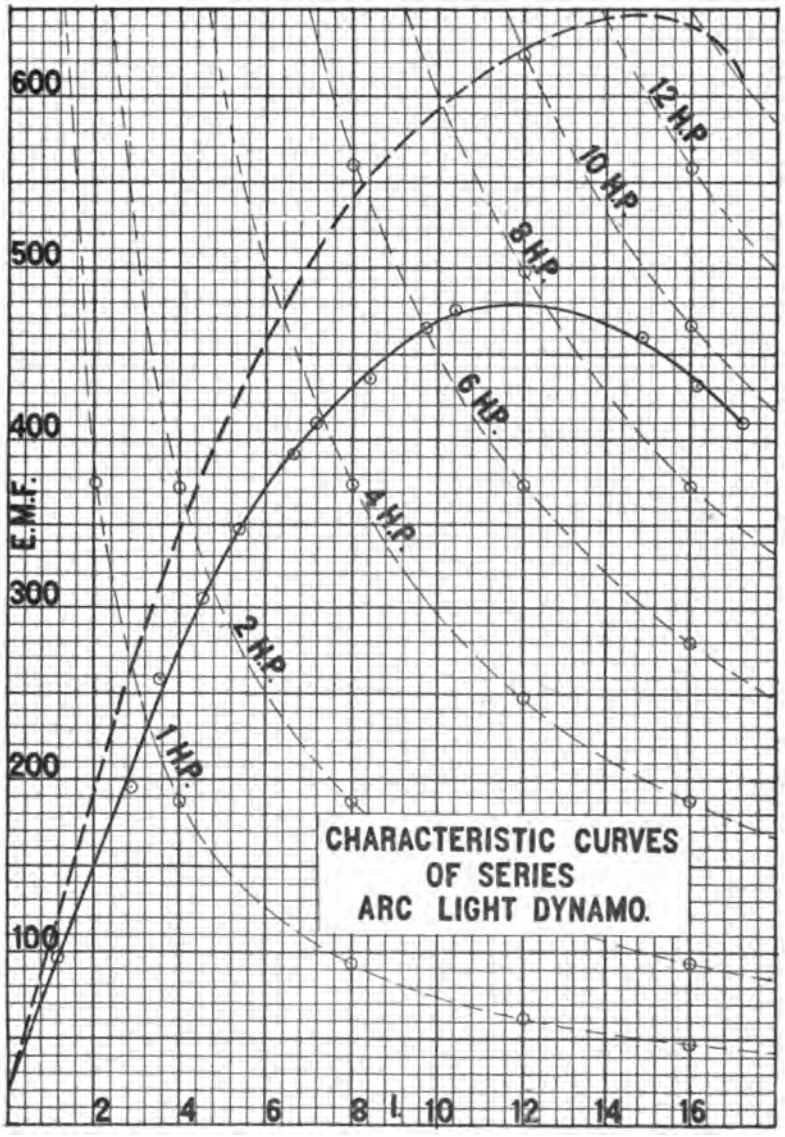

600
500
400
300
200
100
E.M.F.
12 H.P.
10 H.P.
8 H.P.
6 H.P.
4 H.P.
2 H.P.
1 H.P.
CHARACTERISTIC CURVES
OF SERIES
ARC LIGHT DYNAMO.
2
4
6
8
10
12
14
16

Fig. 3.

variable resistance, there must be some means provided for raising and lowering the E. M. F.

For effecting such regulation there are these three methods: (1) Varying the speed. (2) Varying the field strength. (3) Changing the position of the brushes.

The first method is seldom made use of although in principle it is very simple. There must be an automatic regulation of speed and the E. M. F. of course rises and falls with it. Such regulation, on account of the inertia of the heavy moving parts of the engine and generator, is too slow for lighting service.

Regulation by the second method is obtained either by changing the number of active conductors in the field or by changing the connections of the coils from series to parallel and *vice versa*. Running on light load (few lamps in series) only enough turns in the field are left in circuit to maintain a current of 10 amperes, and as more lamps are added to the circuit more field turns are thrown in to strengthen the field and to raise the voltage. The disadvantage of this method is the small range of loads that can be economically carried. For as the field coils are thrown in the cores soon rapidly approach the point of saturation, beyond which a large increase of ampere-turns effects the E. M. F. very slightly. On the other hand the machine will not run well on very light loads, for the current being constant the reaction of the armature is constant and on the weakened field has a greatly increased effect of distortion upon the field and causes serious sparking at the brushes.

The third method, that of shifting the brushes, is the most common one. To understand the principle of this regulation it will be well to refer back to the figure showing the two paths of the current through a ring armature and out by the brushes (see illustration in section devoted to "Theory of Dynamo-Electric Machinery"). It will be seen readily that the maximum E. M. F. at the brushes is obtainable when they are at the neutral point, that is when all the amature coils on either side of the brushes generate an E. M. F. in the same direction. If the brushes are shifted from the neutral point then some of the coils on either side oppose the others on the same side and a reduced pressure at the brushes is the result. If the brushes were placed at points midway between the neutral

points, then on each side half the coils would oppose the other half, and the pressure at the brushes would be nil; that is, the algebraic sum of the E. M. F.'s of the coils in each half would be zero. Then by moving the brushes from this point toward the neutral point, this sum, or the E. M. F. of the machine, would increase gradually to the maximum. Such is the principle of this method of regulation.

A constant current machine running on light load will have its brushes in a position considerably off the neutral point, and as more lights are thrown into the circuit, making the load heavier, they will be brought correspondingly nearer, maintaining sufficient E. M. F. at the brushes to force a current of constant value through the increasing external resistance. The shifting of the brushes is done automatically by electro-magnets in circuit, which act instantly to counteract any change of current strength flowing through them.

In practice various devices are used by different makers to accomplish the regulation. In some machines the position of the brushes on the commutator is altered by a mechanism controlled by the current; in others the controlling mechanism alters the field strength by short-circuiting some of the coils, or by increasing or decreasing a resistance placed as a shunt around the field, thus varying the value of the current in the field coils instead of the number of turns. The variable brush method is sometimes combined with the variable field method. A description of some forms of arc lighting machines, together with their regulators, is given in a following section.

Saturation Curve. To obtain a certain magnetization by a field coil, it is immaterial whether the coil consists of a small number of turns carrying a large current, or of a large number of turns carrying only a small current. As long as the product of the number of turns and amperes passing in them, or **ampere-turns**, is the same, the magnetization produced will be of constant value. Thus a coil of 100 ampere-turns may be made up of one turn of a large heavy wire carrying 100 amperes, or it may be made up of 100 turns of fine wire carrying one ampere, and the magnetizing force which will be exerted will be exactly the same in either case. Magnetizing forces are therefore sufficiently ex-

pressed by the number of ampere-turns in the magnetizing coil.

The saturation curve of a dynamo shows to what intensity the field magnets have been magnetized, and thus whether they are properly designed. The curves are formed by plotting points whose abscissæ are values of ampere-turns in the field coils, and whose ordinates are the corresponding values of the voltage, these points being plotted for varying values of the current. The readings may be observed for both ascending and descending values of the current, thus showing the effects of hysteresis.

From an economical standpoint it is best not to carry the magnetic flux too near the point of saturation during normal working, for the number of ampere-turns required to produce a given magnetic flux is greater in a saturated field than in one not saturated. In certain types of machines, however, there are certain advantages in practical points of working and regulation to be derived from having saturated fields that are of such importance as to outweigh the value of greater efficiency. By knowing from the type and the design of a machine to what degree its fields should be saturated, and by having an experimental saturation curve of the machine, a comparison can be made between the ideal and the result. Fig. 4 gives the saturation curves of the magnetic circuit of a Crocker-Wheeler dynamo for no load and with load, and for increasing and decreasing values of the current, the dynamo running at a constant speed of 1,620 revolutions per minute. The total characteristic curve of the simple series dynamo is only a slightly modified saturation curve, as will be seen from a comparison of Fig. 2 and Fig. 4. But in dynamos provided with regulators, the operation of these appliances changes the form of the characteristic very markedly.

THE SHUNT DYNAMO.

The shunt dynamo is so named because the coils which excite the field, instead of being connected in series with the outside circuit, form a shunt about it, the field circuit and outside circuit being connected in parallel at the brushes (see Fig. 5).

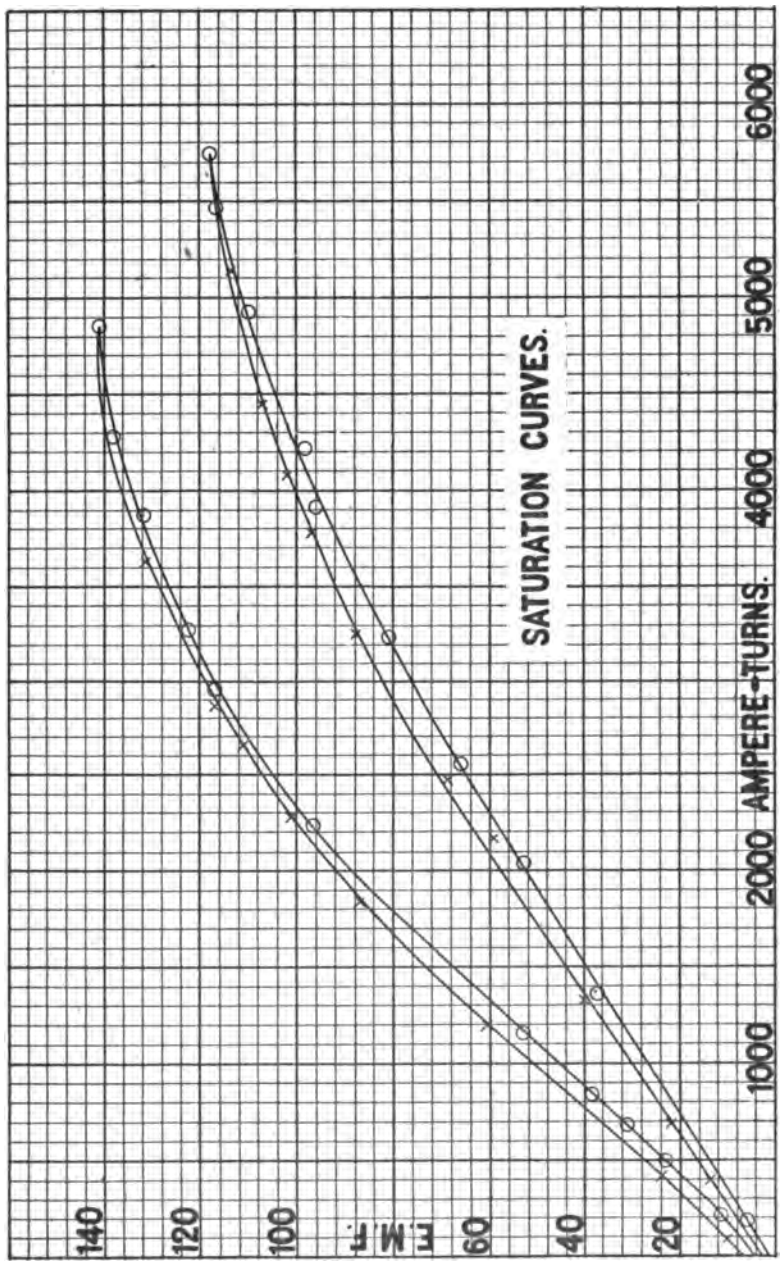

SATURATION CURVES.
2000 AMPERE-TURNS.
1000
4000
5000
6000
140
120
100
80
60
40
20

Fig. 4.

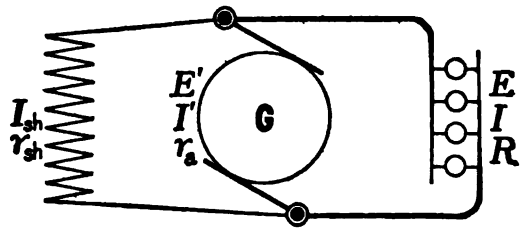


Fig. 5. Diagram of Shunt-Wound Dynamo.

As in the case of the series dynamo, the properties of the shunt machine can be best explained with the aid of characteristic curves (see Fig. 6). There are three characteristic curves to be considered, the **external,** in which the volts at the terminals are plotted against the amperes in the outside circuit, the **internal,** in which the volts at the terminals are plotted against the amperes in the shunt circuit, and the **total** in which the total volts generated by the machine are plotted against the total current. The total characteristic differs from the external only in that the volts are obtained by adding to the volts at the brushes the drop in potential through the armature. This drop in volts is equal to the current passing in the armature multiplied by the armature resistance. The total current is obtained by adding the current in the shunt circuit to that in the outside circuit. The internal characteristic taken with the outside circuit open is like the curve for a series dynamo. It rises steeply at first and then bends over as the saturation of the magnets begins to be noticeable. In fact with the outside circuit open the machine is a series dynamo with all its circuit in the field coils.

The external characteristic curve is a loop. It begins at maximum voltage and zero current, and extends almost horizontally at first, then slopes down more and more, turns rather suddenly, then doubles back and tends to approach the origin. When the dynamo is started the outside circuit is open and there is no current through the armature. As soon as it is built up the armature is generating only the current for the field coils which, as we have seen, is very small owing to the great resistance of these coils. But the small current produces only an insignificant drop in the armature so that the voltage at the brushes is nearly the total generated by the armature. Hence the current in the field coils is as great as it can ever become which makes the field magnetism and consequently the E. M. F. generated by the armature a maximum. Now suppose that a number of lamps (connected in

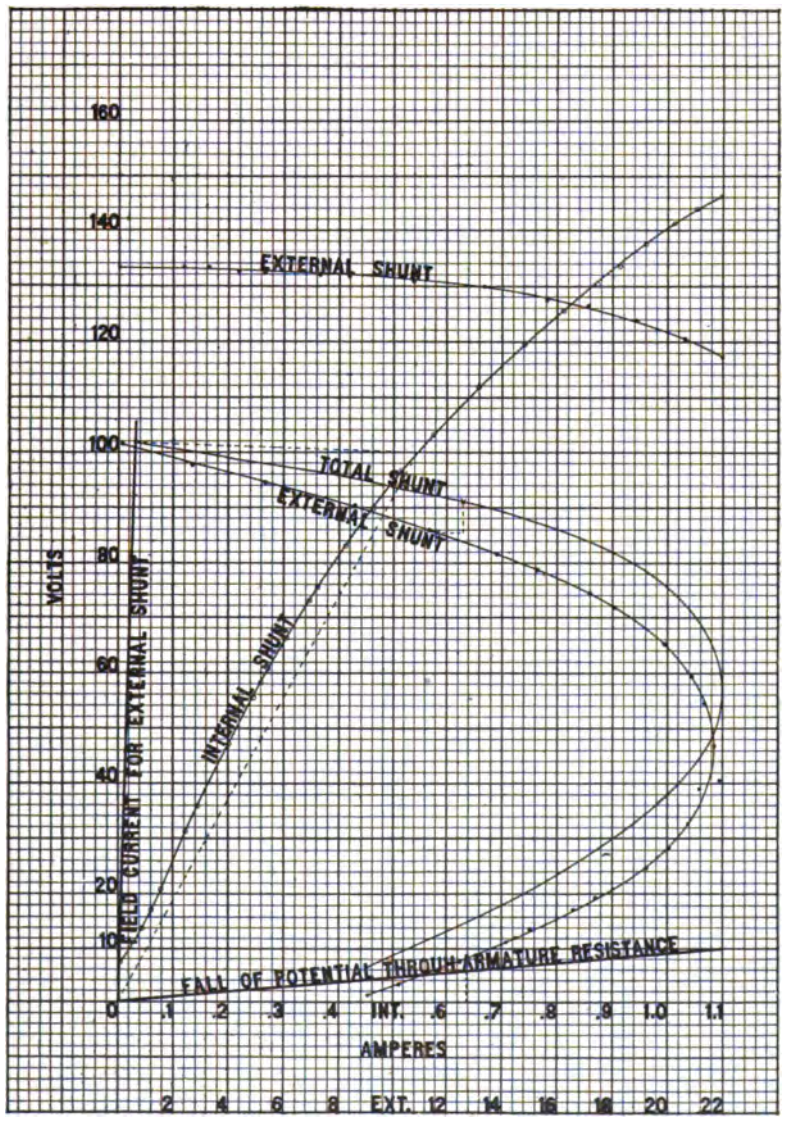


Fig. 6. Total, External and Internal Characteristic Curves of Shunt Dynamo.

parallel across the leads from the machine) are thrown on the machine. A current flows at once, and as a result there is a drop through the armature so that there is a little less voltage available at the brushes to excite the field coils, which means a slight dropping of the total voltage. If more lamps are connected in parallel, the existing voltage at the terminals will act for an instant, and furnish them with as much current as those already on are receiving, but the greater current means increased drop in the armature which, as explained above will again bring down the total voltage generated. With less voltage at the terminals the total current will diminish a little. Therefore lowering the resistance of the circuit by the addition of lamps in parallel lowers the available voltage, because it increases the amount of the volts lost in the armature. By building the armatures with an extremely low resistance it is possible to make machines for which the drop in terminal pressure is not very noticeable over quite a large range of load. It is for this reason that a shunt machine is used for incandescent lighting where it supplies an approximately constant voltage. The dynamo would be designed for such a voltage that at low loads the voltage would be a little too high while at heavy loads it would be a little too low. In actual lighting work, however, the resistance of the field coils is made somewhat less than would be necessary to give the right voltage. This is accomplished by using a larger size of wire than necessary, the number of turns remaining the same.

By inserting a **rheostat,** or resistance which can be varied at will, between the field coil and one of the brushes, the current in the coil can be cut down to the proper value under normal conditions, and when the load increases and the effective voltage tends to drop, it is only necessary to cut out some of the resistance in the rheostat to obtain more current, and consequently greater excitation in the field coil, thereby raising the voltage to its normal value again. The rheostat (see Fig. 7) consists generally of a resistance with connections at short intervals along it and terminating in metal contacts arranged in a circle. A sliding contact piece is moved over them by the handle, introducing the current at any point on which the sliding contact is resting. In this way the amount of resistance in series with the field coil may be regulated with great exactness.

This regulation is generally effected by hand, the resistance being decreased when the voltmeter shows that the voltage is falling on the line, and vice versa. By means of regulators, magnets, solenoids and various electrical and mechanical means this regulation is sometimes made automatic.

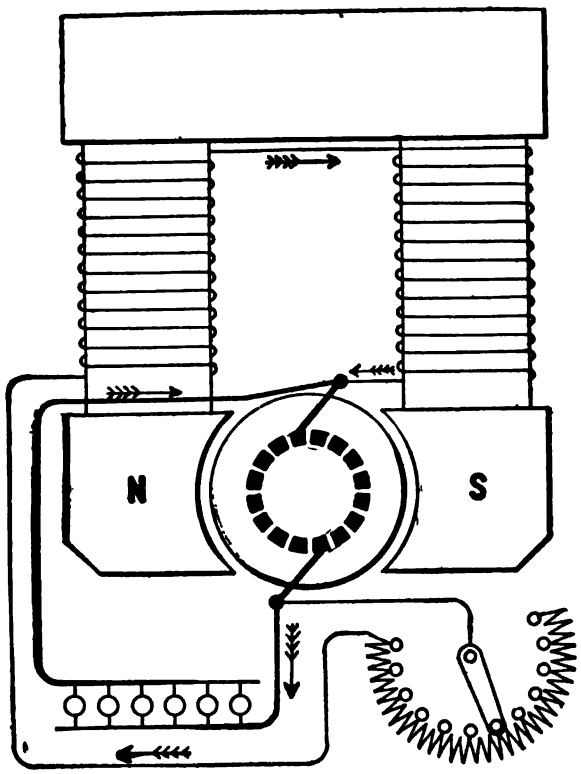


Fig. 7. Dynamo and Rheostat.

Returning to the characteristic, it is interesting to note that the continued increase in load on the machine, due to decrease of external resistance, causes the voltage to fall more and more rapidly until a point is reached where a decrease in circuit resistance can throw no more load on the machine, because the decrease in voltage is so rapid as to unbuild the machine. Theoretically the curve would come down to the origin; it does not, practically, however, owing to residual magnetism.

The resistance of the outside circuit corresponding to any point on the characteristic curve can be found very readily. The voltage divided by the current gives the resistance. By drawing a straight line (see Fig. 8) from the origin or the point where the current and voltage are 0 through the point corresponding to 50 volts and 50 amperes it will intersect the characteristic curve at a certain point. It is obvious from the figure that the voltage at this point just equals the current, and so the resistance here is 1 ohm. Similarly by drawing a line from the origin through the point where voltage is 100 and current 50 the characteristic curve is intersected at another point and the resistance of the circuit at this point is 2 ohms. A scale of resistance may be marked on the vertical line corresponding to 10 amperes. By drawing a line from any point on the characteristic curve to 0, the point of intersection on this resistance scale line gives the resistance of the outside circuit. The characteristic curve shown in Fig. 6 is for a small shunt dynamo which being run at 630 revolutions gave a maximum of a little less than 2 horse-power at 68 volts and 19.2 amperes. With a decrease in resistance much below $2\frac{1}{2}$ ohms the current increases but little, whereas the voltage falls a great deal. If the external resistance becomes less than 1 ohm the machine loses its voltage and current immediately and will not build itself up again until the resistance is increased. The most critical part of this curve is where the voltage is about 30 or 31 and any given change of resistance at this point will alter the voltage more than at any other part of the curve. By increasing the resistance the voltage is steadily increased until it gets to its maximum when the external circuit is open and the resistance is infinite, the whole voltage being then available for magnetizing the shunt field coils to their maximum strength.

Fig. 8 shows the characteristic curves of a shunt-wound Gramme dynamo capable of giving 400 amperes at 120 volts. The armature conductors were not capable of carrying more than 400 amperes, and the part of the curves not actually found by experiment is shown in dotted lines. The lower curve marked E is the external characteristic while the upper curve marked E' is formed from it by adding to the external voltage at any point the corresponding value of the voltage lost in the armature at the given time.

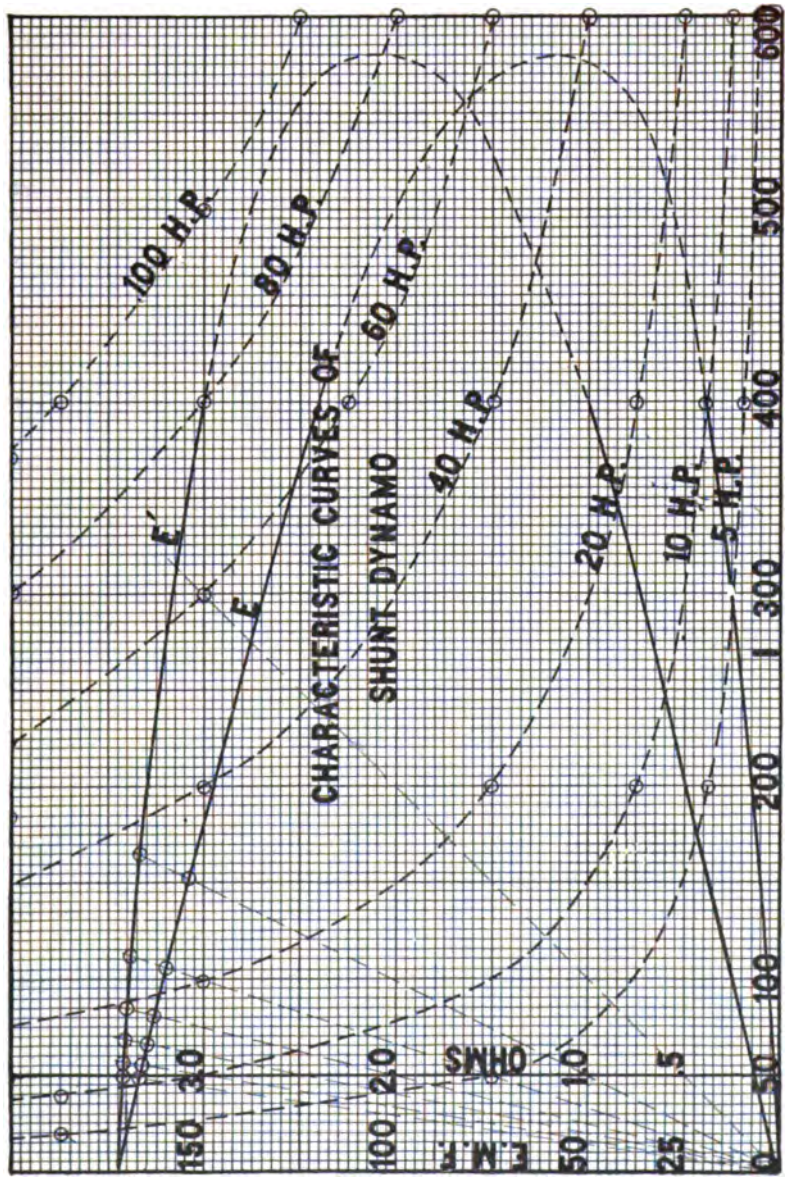


Fig. 8. Characteristic Curves of Shunt-Wound Gramme Dynamo.

Both series and shunt machines have critical points, but the series machine will act only with the resistance of the circuit less than a certain amount while the shunt machine will work only with it greater than a certain amount. With the series machine, increase in the number of lamps in series decreases the ability of the machine to maintain its load, increase in the number of lamps in parallel increases the ability of the machine to generate and consequently increases the current per lamp. With the shunt machine an increase of the lamps in series increases the ability of the machine to furnish current, while increase in the number of lamps in parallel decreases the ability of the machine to supply current. These opposing characteristic qualities are made use of to secure a machine which is automatic in its ability to furnish a constant potential under widely varying loads.

THE COMPOUND DYNAMO.

Electrical energy for incandescent lights, power circuits, and railways is supplied by constant potential dynamos, that is by machines which are so constructed that they will deliver current varying in amount between zero and the limit of their capacity and at the same time maintain a pressure at the terminals that is very nearly uniform.

Though a shunt machine comes nearer to fullfilling the requisite conditions than a series, still neither are self-regulating. The shunt machine with a variable resistance in series with the field coils, has been used as described on a previous page. There are also other arrangements which could be used to attain the same end but as they have not found favor in practice they will not be considered here.

It has been shown how with the shunt machine, owing to increase in current, the volts lost in the armature are increased, resulting in decreased ability to sustain the output. To make a shunt machine self-regulating some means must be provided for increasing the field strength with the increase of the strength of the current. This can be easily accomplished by winding on the field magnets a coil consisting of a few turns of heavy wire through which the whole current of the circuit can be passed. This series coil is sometimes called the compensating coil because it compen-

sates for the weakening tendency when the shunt coil alone is used. A machine with such a winding is called a **compound-wound machine.** Being a combination of the series and shunt machines, its characteristic curve is a combination of the two, the

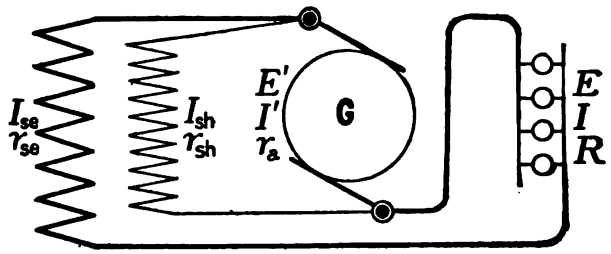


Fig. 9. Ordinary, or Short Shunt Compound Dynamo.

rise in the characteristic of the series machine occurring at the point where that of the shunt machine decreases.

There are two methods of connecting up a compound-wound machine, called respectively **short shunt** (see Fig. 9) and **long shunt** (see Fig. 10), according as the shunt terminals include the armature, that is, connected from brush to brush, or the series coil in addition, that is, connected from brush to end of series coil. It

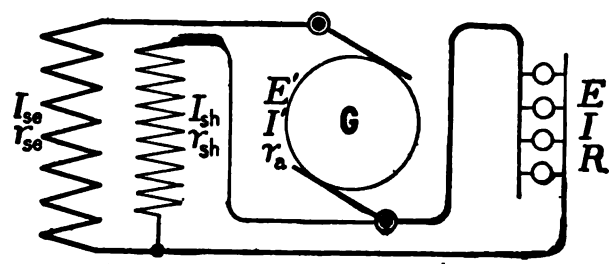


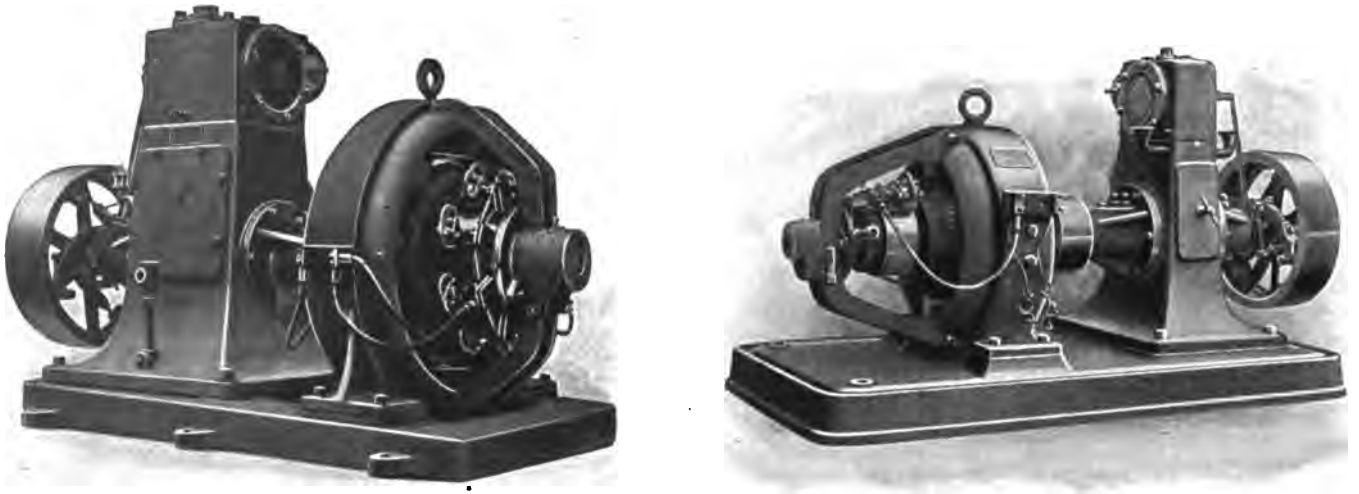
Fig. 10. Long Shunt Compound Dynamo.

makes very little difference in practical results which form of connection is employed, since the resistance of the series coils is always very small. The characteristic curve of a compound machine generally approaches a horizontal line, often it rises slightly at the beginning and then continues nearly horizontal throughout the range of loads that it is required to carry.

As the load increases and the resistance of the outside circuit decreases the main current in the series field coils increases and the current in the shunt coils still remains constant as it is now fed with a constant voltage. Thus although there are more lost volts in the armature to cut down the voltage, and although there is a much greater demagnetizing effect produced by the armature yet the voltage supplied to the external circuit is still maintained constant. A compound dynamo therefore if properly proportioned, will supply a practically constant voltage at all loads. In the case of the ordinary or short shunt compound dynamo, the potential at the brushes is kept constant. In the case of the long shunt dynamo the potential at the terminal of the working circuit is constant. The latter arrangement therefore is somewhat preferable but either arrangement proves satisfactory in well designed dynamos as the actual value of the difference in the two cases is generally very slight.

In the case of the ordinary or short shunt compound dynamo the series coils furnish the excitation required to produce a potential such as will compensate for the lost voltage in the armature and the demagnetizing effects due to the armature. In the case of the long shunt dynamo the series coils compensate for these same losses as well as for the lost voltage of the series coils.

It is advisable and generally customary to put a somewhat greater number of series turns on the field coils than is necessary to overcome armature reactions and lost voltage in order to have the dynamo give a somewhat greater voltage at full load than at no load. This process which is called **overcompounding** is calculated for a rise of voltage of about four or five per cent. As the load increases an engine often runs a few revolutions slower, or there is a trifle more slipping of the belt which causes the speed of the armature to drop a little; the increasing load is also accompanied by a greater lost voltage in the line or feeders; hence the dynamo should be overcompounded to make up for these losses. If the load is at some distance from the generator there might be considerably more than 5% drop of voltage at full load. This drop can be figured and a machine may be especially compounded for this loss at the time it is built. The object of course is to keep the voltage constant at the lamps, and if they are some distance



Direct-Driven Generating Sets.
(By Courtesy of C. & C. Electric Company.)

away and the load is constantly changing it is often necessary and advisable to run so-called *pressure wires* from the center of distribution back to a voltmeter in the dynamo room. Then if the dynamo is not overcompounded so as to give the proper pressure at all loads the pressure may be varied by adjusting the rheostat which is in series with the shunt coils of the dynamo. Even though the dynamo is properly compounded it is almost always necessary to regulate with the rheostat also in the case of incandescent lighting, especially where the lamps are distributed over a wide territory.

In designing a dynamo for any given output it is necessary to make due allowance for the total energy to be generated which is the total voltage E' multiplied by the total current I'. In order that the energy lost in the series field turns may not be too great, it is well to have them wound near the field cores so that each turn may be as short as possible and then the shunt coils may be wound outside of the series turns.

In Fig. 11 are shown some characteristic curves of a compound-wound Crocker-Wheeler dynamo running at 1500 revolutions per minute.

The upper curve is the external characteristic of the dynamo running with all the resistance cut out of the shunt field regulating rheostat. It is running, therefore, with a maximum field excitation and giving its maximum voltage, about 127.8 volts at no load. It will be noted that as the load increases the voltage drops somewhat. It is evident that the magnetic flux due to the series ampere-turns on the field coil is not great enough to make up for the armature demagnetizing effects and the lost volts in the armature. Therefore there are not enough series turns, and the dynamo is undercompounded when running at 127.8 volts.

Next some of the resistance of the regulating rheostat is put in series with the shunt field until the voltage falls to 109.2 volts. By increasing the load the voltage increases, being from about 4 % to 7 % higher as the load increases than it was at no load. Now the rise in voltage, due to compounding, makes up for the loss in the line wires and is a little too great in the case of the 7 %, and in order to keep the lamps from burning too brightly the rheostat handle would have to be turned so as to cut the voltage down a little.

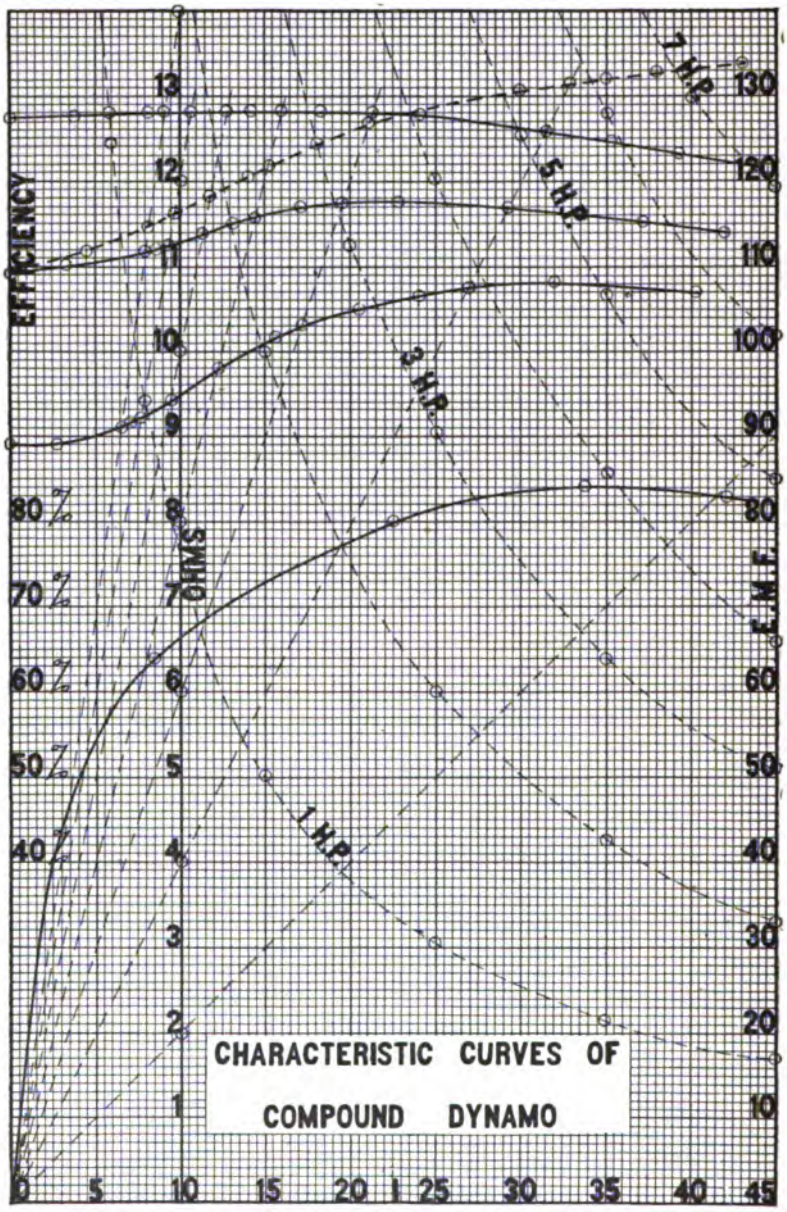


Fig. 11. Characteristic Curves and Efficiency Curve of a Crocker-Wheeler Compound Dynamo.

Judging from these two curves it appears that if the dynamo were run at a little higher initial voltage, say 112 or 115 it would be then running at just about the proper voltage for which it was compounded. The percentage of the overcompounding would then be about four or five per cent and the dynamo might run at varying loads with little or no need of adjusting the rheostat.

The curve shown by broken line (see Fig. 11) is the total characteristic curve derived by adding the values of the lost volts in armature and in series field to the value of the external voltage.

The lower compound characteristic curve starting with an initial voltage of 89 shows that the dynamo is very much overcompounded when running at this voltage. The rheostat has been so adjusted that less current flows through the field coils, the shunt current is reduced and the value of the shunt ampere-turns is reduced. On the other hand the value of the series ampere-turns is as great as formerly as the load increases, and so the value of the series excitation is now large in comparison with that of the shunt. The voltage therefore increases greatly with the load, causing the dynamo to be greatly overcompounded when started at an initial voltage of 89.

In Fig. 11, is also given a curve of commercial efficiency for this 5 H. P. Crocker-Wheeler compound dynamo, the commercial efficiency being the useful electrical work, $E\,I$, derived from the dynamo, divided by the value of the mechanical work delivered to the pulley of the dynamo.

The following table contains the data from which the characteristic curves shown in Fig. 11 were drawn.

I	E	I	E	I	E
0	127.8	0	109.2	0	89.
3.6	128.0	3.4	110.0	2.7	89.7
8.4	128.0	8.7	112.0	7.2	91.8
14.2	127.7	13.2	115.0	11.3	96.4
18.4	127.7	17.1	117.0	15.6	101.8
23.8	127.6	22.6	117.0	20.6	105.0
27.2	127.2	25.6	116.8	24.6	105.4
30.9	126.0	29.3	116.0	27.9	107.5
35.2	124.0	33.7	116.0	32.0	108.2
39.3	122.9	37.1	115.9	36.1	108.0
43.8	121.9	42.8	114.0	40.3	107.0
				40.4	107.0

The characteristic curves of a 5 K.W. Edison compound

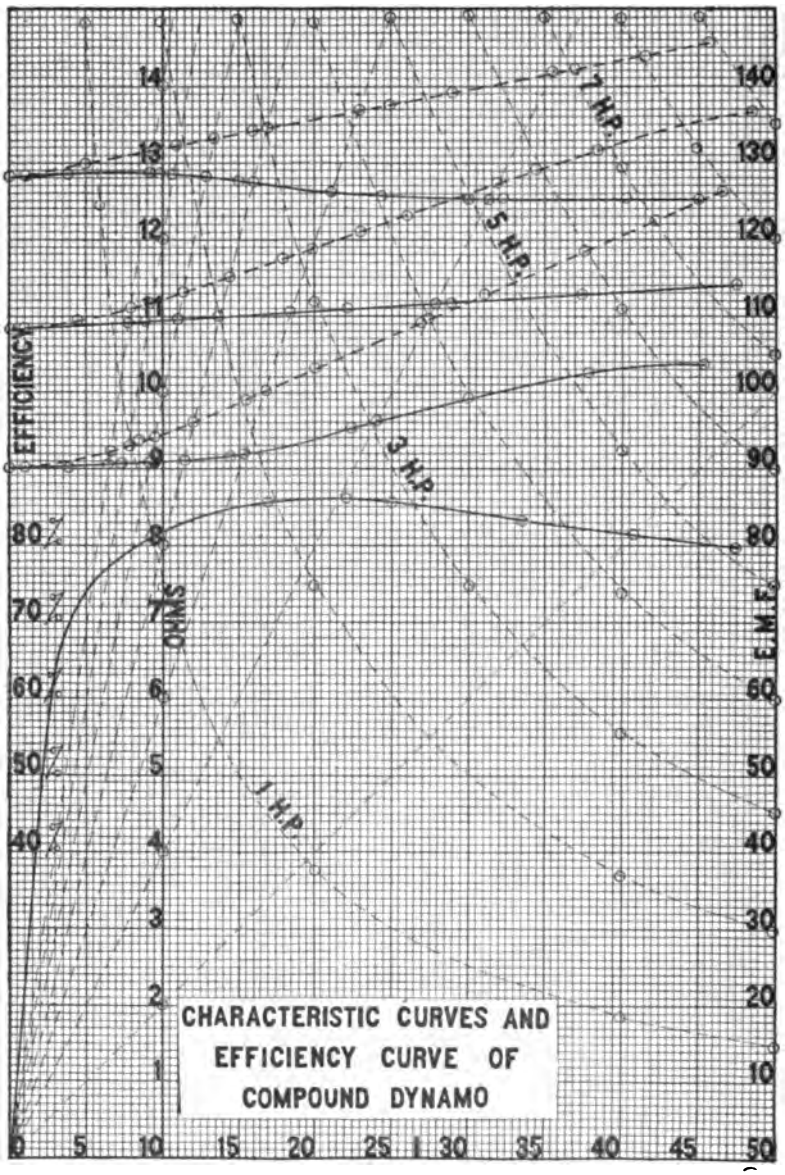


Fig. 12. Total and External Characteristic Curves and Efficiency Curve of 5 K. W. Compound Edison Dynamo.

dynamo are given in Fig. 12, for initial voltages of 131, 110, and 90, at a speed of 1,700 revolutions. In testing dynamos it is very difficult to keep the speed absolutely constant. There may be a variation in the speed of the main pulley from which the dynamo is run, and the belt may slip more and more as the load increases. However, as the voltage is proportional to the speed, the observed voltage may be corrected for the observed speed quite readily. The reading of the voltmeter and the tachometer should both be taken at the same instant.

The characteristics of the compound Edison dynamo as shown in Fig. 12, present very much the same phenomena as were exhibited by the characteristics of the Crocker-Wheeler dynamo in Fig. 11. The Edison dynamo, the curves of which are shown, is probably properly overcompounded for about 4% or 5% when running at an initial voltage of about 115. A curve of electrical efficiency is also shown.

The following table gives the data for the characteristic and efficiency curves of the 5 KW. compound Edison dynamo.

Speed.	E	E corrected to 1,700 rev.	I	Speed.	E	Corrected E	I	$\frac{E\,I}{E_1 I_1}$
1740	131.5	128	0	1720	110	108.1	0	0
1725	130.0	128.1	8.8	1715	111	109.3	8.7	.82
1730	130.0	128.3	9.8	1690	111	111.0	22.0	.86
1725	128.5	126.7	14.7	1670	110	111.3	28.7	.87
1720	128.0	126.6	19.2	1665	112	113.1	37.3	.82
1715	126.5	125.4	24.3	1660	112	114.0	47.5	.80
1710	126.5	125.6	28.0	1730	91.5	90.0	.0	
1705	125.5	125.3	32.2	1730	91.5	90.0	7.4	
1685	124.0	125.2	36.0	1725	93.0	91.6	14.6	
1670	123.0	125.3	40.3	1715	96.5	95.7	22.4	
1665	123.0	125.6	45.0	1685	99.0	99.9	30.0	
1635	118.5	123.3	46.5	1660	99.5	101.9	38.0	
				1640	100.0	103.7	45.4	

THE MAGNETIC CIRCUIT.

Every dynamo-electric machine or electrical instrument whose working depends upon the laws of magnetic induction, must have a complete magnetic circuit just the same as it has a complete electric circuit. Moreover the laws governing the magnetic circuit are similar to the laws governing the electric circuit. The one important difference between the magnetic circuit and the electric circuit lies in the difference of materials of which the two

are composed. Every substance is a conductor of electricity to a certain extent; there is no perfect non-conductor or insulator. The best conductors are metals and graphite. Dry air, dry wood, mica, rubber, etc., are such very poor conductors of electricity that they are called insulators or non-conductors.

Almost all substances are fairly good conductors of magnetism. Iron and steel in their various forms are *excellent* conductors, and nickel, cobalt and oxygen lie between these and the fairly good conductors in their magnetic qualities. Fairly good conductors include solids, liquids and gases, metals and non-metals, organic and inorganic substances; and with the exceptions named above and a few others, they are *equally* good conductors. Air is generally taken as the standard and is neither a better nor a poorer conductor than gold or copper.

The greater the current in an electric circuit the greater is the amount of energy required to cause the current to flow, provided the resistance remains unchanged. In like manner the amount of energy required to produce a magnetic flow in air is proportional to the strength of the magnetic field produced. Iron and steel however have induction coefficients which are very important in their bearings. When an electromagnet is weakly magnetized the amount of electrical energy required is nearly proportional to the strength of magnetism. After the metal begins to be **saturated** with magnetic lines, the amount of electrical energy required to increase the magnetism becomes much greater than formerly. After the metal has become strongly saturated with magnetic lines even a large increase in the electrical energy supplied may produce almost no increase in the magnetic intensity.

In order to have an electric flux or electric current in an electrical circuit it is necessary to have an electromotive force. Similarly in order to have a magnetic flux or magnetic field it is first necessary to have a **magneto-motive force**, (M. M. F.). Lodestones and other so called permanent magnets have a magneto-motive force that keeps up a magnetic flux or field constantly. By passing an electric current through an electric circuit a magneto-motive force is induced at right angles to the path of the electric conductor. In the electric circuit a given E. M. F. will cause a larger current to flow through a low resistance conductor

than through a high resistance conductor. Similarly with a given M. M. F., a greater magnetic flux is produced in a good magnetic circuit of iron or steel than in a poor magnetic circuit of air or copper.

The geometrical distribution of the magnetic lines of force about a conductor carrying a current is shown in Fig. 8, which gives an end view of the conductor. The current is assumed to be flowing toward the observer, and the direction of the magnetic flux is shown by arrows. As shown by the flux paths 1, 2, 3, 4, 5, the magnetic density is greater near the wire, diminishing rapidly in strength farther from the conductor. The mathematical law of this diminution is as follows: the intensity varies inversely as the distance from the conductor.

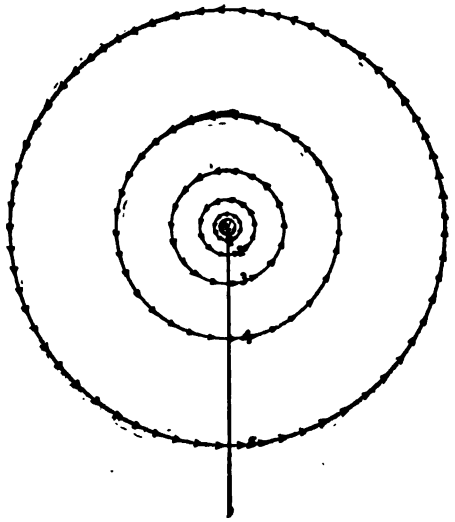


Fig. 8.

If an electric conductor is bent into the form of a loop and an electric current of one ampere passes through the conductor then a certain number of magnetic lines of force pass through the loop. After following curved paths they will return to the loop passing through it again in the same direction as at first. Now if two amperes flow through this conductor, or the same current (one ampere) flows through two similar conductors laid side by side, then in either case just twice as many magnetic lines will flow through the loop as in the first case. Therefore the intensity of the magnetic flux through a loop composed of an electric conductor carrying a current, depends upon and is directly proportional to the number of **ampere-turns.** This magnetic flux can be made very great either by forcing a large current through the conductor, or by having a very large number of turns in the loop, or by both.

The absolute unit of current being ten times the ampere, the ampere-turn is only one tenth the value of the current-turn. Of the two, the ampere-turn is in more common use as a practical unit. The fundamental unit of M. M. F. in the United States is called the **gilbert,** and is produced by $\frac{1}{4\pi}$ of a C. G. S. unit or current-turn, or by $\frac{10}{4\pi}$ ampere-turns. Therefore by dividing the number of ampere-turns in any coil by $\frac{10}{4\pi}$, the M. M. F. of the coil is obtained in gilberts.

The quantity of magnetic flux in any magnetic circuit depends upon the M. M. F. and upon the nature and form of the circuit. In an electric circuit the current produced by an E. M. F. depends upon the resistance of the circuit. Similarly in a magnetic circuit the magnetic flux produced by a M. M. F. depends upon the **magnetic reluctance** or simply **reluctance** of the magnetic circuit. Magnetic reluctance is similar to electric resistance and is often defined as *the resistance of a circuit to magnetic flux.*

The resistance of an electric circuit measured in ohms is equal to the **specific resistance** or **resistivity** of the conductor, multiplied by the length and divided by the cross section of the wire. Similarly, the reluctance of a magnetic circuit, measured in **oersteds,** is equal to the **specific magnetic resistance** or **reluctivity** of the magnetic conductor, multiplied by its length in centimeters, and divided by its cross section in square centimeters. The reluctivity of a vacuum is unity and the reluctivity of air is generally considered equal to unity although it varies slightly. All other non-magnetic substances such as brass, copper, glass, wood, and water also have a reluctivity which is practically equal to unity. The reluctivity of magnetic metals such as iron, steel, nickel, and cobalt vary quite widely from unity and their values also vary quite widely among themselves.

The unit of reluctance by which the magnetic resistance of a circuit is measured is called an **oersted,** and is defined as the reluctance or magnetic resistance of a cubic centimeter of air measured between two opposite faces, hence the reluctance of a

column of air 20 cm. long and 2 cm. square (4 sq. cm.) is 5 oersteds.

In the electric circuit,

Electric flux (in amperes) =

$$\frac{\text{Electromotive force (in volts)}}{\text{Resistance (in ohms)}}, \quad \text{or } I = \frac{E}{R}.$$

In the magnetic circuit,

Magnetic flux (in webers) =

$$\frac{\text{Magneto-motive force (in gilberts)}}{\text{Reluctance (in oersteds)}}, \quad \text{or } \Phi = \frac{\mathfrak{F}}{\mathfrak{R}}.$$

If a non-magnetic ring (see Fig.14), is uniformly wound with insulated wire, and a current is passed through the wire, the magnetic circuit will be completely closed by the coil or solenoid, and no magnetic flux will leak outside of the coil. If the cross section of the ring is 15 sq. cm., and the mean circumference is 45 cm., the reluctance of the magnetic circuit will be $\frac{45}{15} = 3$ oersteds. If the number of turns of wire is 100 and the current 5 amperes the M. M. F. in the magnetic circuit will be 500 ampere-turns, or $500 \div \frac{10}{4\pi} = 628.32$ gilberts. The magnetic flux in webers will be

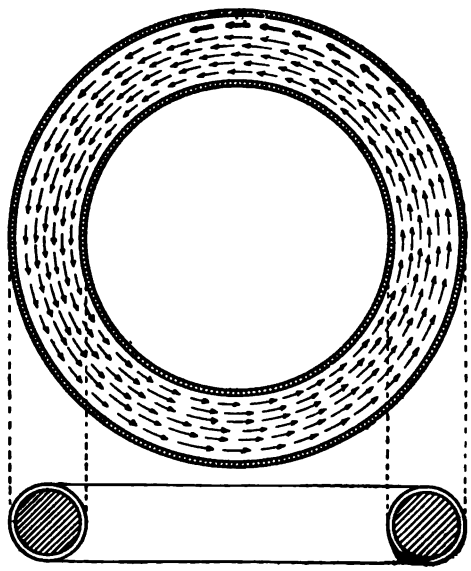


Fig.14.

$$\frac{628.32}{3} = 209.44 \text{ webers.}$$

The weber is the *magnetic line* of the preceding section.

The greater part of the magnetic circuits in dynamos consists almost entirely of iron. The reluctivity of iron and steel varies greatly, according to hardness and chemical composition, and also the degree to which it has been magnetized. When iron is fully saturated magnetically its reluctivity is as great as the reluctivity of air. The reluctivity of soft iron or steel, when it is not strongly magnetized, is often several thousand times less than that of air. The ferric magnetic circuit is an easy one to calculate, however, since the magnetism is confined almost exclusively to the iron, thus giving a magnetic circuit of definite and easily computed length and cross-section.

There is some leakage of magnetic flux from the iron into the air. For dynamos of ordinary sizes and shapes it varies from 15% to 30% of the flux through the field coils. It may be separately calculated and allowed for.

The **magnetizing force**, represented by the symbol $\mathfrak{H}$, may be defined as the rate at which the magnetic potential diminishes in a magnetic circuit. The total fall of magnetic potential in a magnetic circuit is equal to the M. M. F., just as the total fall or drop of electric potential in an electric circuit is equal to the E. M. F. The total difference of magnetic potential in the magnetic circuit shown in Fig. 14 is 628.32 gilberts. As this circuit is symmetrical and uniform throughout, the drop of magnetic potential is uniform and equal for each unit of length. The mean length of the circuit being 45 cms., the rate of fall of potential is about 14 gilberts per centimeter all around the circuit. This is the magnetizing force, or the magnetic force, represented by $\mathfrak{H}$. When there is no iron or other magnetic substance in the circuit, the value of the magnetizing force $\mathfrak{H}$ is equal to the flux density $\mathfrak{B}$.

If in any magnetic circuit the M. M. F. expressed in gilberts is divided by the length of the magnetic circuit in cms., the average value of the magnetizing force will be obtained. Thus in a long helix, if there is a M. M. F. of 500 gilberts, and the magnetic circuit inside the helix has a length of 50 cms., the magnetizing force will be 10 gilberts per centimeter, and the flux density will be 10 gausses, provided there is no magnetic substance in the circuit.

If there is iron or any other magnetic substance in the circuit the magnetizing force will still remain 10 gilberts per centimeter although the magnetic flux density will be greatly increased according to the permeability of the magnetic circuit.

FORMS OF FIELD MAGNETS.

The function of the field of a dynamo is to provide a space filled with lines of magnetic induction which the conductors of the armature may cut, thus causing an electromotive force to be generated in them. It is immaterial to the generation of an electromotive force whether the armature or the field revolves, though generally the field is stationary. It is usually desirable to maintain the magnetic induction or number of magnetic lines at constant value. The first field magnets to be used were permanent steel magnets, and small dynamos are still built with them. The magneto-machine is a shuttle-wound dynamo having its field produced by permanent magnets. Such machines can not, of course, have as large a capacity as others equipped with electromagnets, and they are subject to loss of magnetism which after a while is liable to render them useless unless they are remagnetized. The fields of modern dynamos are supplied by electromagnets, connected to the circuit of the dynamo according to the purpose for which it is built. The different forms, named according to the winding are, — the magneto, the separately excited machine, the series machine, the shunt machine and the compound-wound machine.

The separately excited dynamo has its field coils fed from some outside circuit. This form of winding is not used much with direct current machines except for special cases. Its place is with alternate current machines where it is inconvenient to excite a machine by its own current.

Field magnets for dynamos and motors have been made in almost every conceivable shape. Electrically speaking the best form to use is one which has the most compact arrangement, presenting the shortest path for the flow of magnetism, the greatest cross section, and the fewest number of joints. Such a form would have the greatest permeability and would consequently be the most efficient. But the form which is most desirable electric-

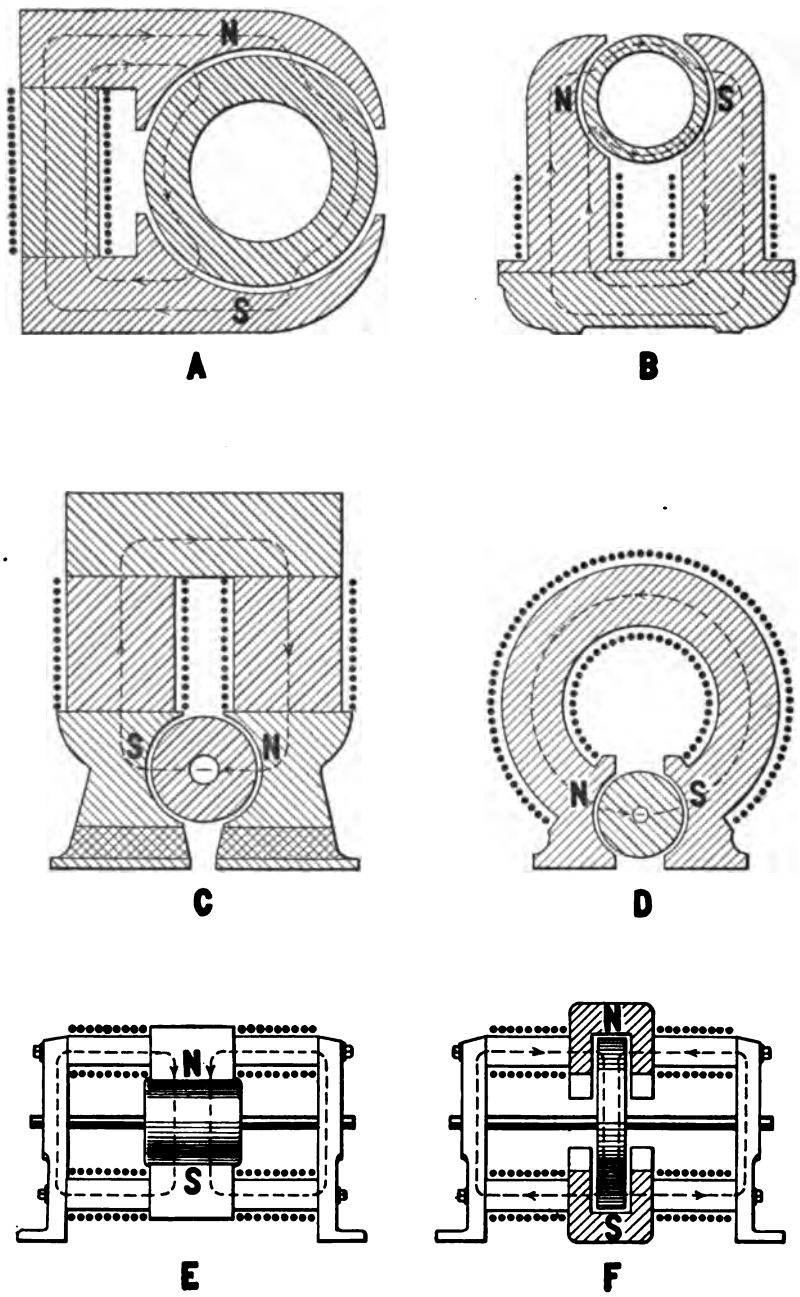


Fig. 15.

ally may often be very difficult and expensive to construct so that the forms which have become fixed in practice are usually the ones which have been found to give the best results at lowest cost.

Some of the more usual forms are shown in Figs. 15, 16 and 17. All types come under three principal heads; the single, the double, and the multiple magnetic circuit.

The horseshoe form is the type of the single circuit bipolar field magnet frame. It is placed upright, C Fig. 15, or inverted, B Fig. 15. The Edison machine is a type of the upright form, which has the disadvantage that it must be mounted on a zinc, brass or some other non-magnetic base, because if the latter were of cast iron, or any good magnetic conductor, the magnetism would be largely diverted by it instead of passing through the armature. The Thomson-Houston machines, now built by the General Electric Co., are of the inverted horseshoe type. The Jenney Electric Co. uses the horizontal type and the vertical form is employed by the Excelsior Electric Co. A modification of the horseshoe magnet type as generally used, is that employed by the Eddy Electric Co., D Fig. 15. In this machine there is no yoke and simply a half ring joins the pole pieces. This gives a very good magnetic circuit but is expensive to build. Another modification is the one magnet form, which has only a single coil wound on the portion of the frame corresponding to the yoke, as A Fig. 15, and this, like its prototype the double coil frame, is made in several positions.

The double magnetic circuit form is equivalent to two horseshoe magnets joined at the poles. The chief advantage of this type is in its greater mechanical strength. The coils are sometimes placed on the two upright sides which connect the top and bottom yokes, as shown by K. Fig 16 and P Fig. 17, the pole pieces being formed on the yokes. Again the pole pieces are elongated to make room for the coils and are placed either vertically or horizontally as shown by G and I. The double magnetic circuit type with internal poles (G Fig. 16) is called *ironclad* and is used in places where the machine might be exposed to accident. A modification of this type is used for street railway motors, the outside connecting pieces are thinned out and spread around the motor so as to completely cover it, affording perfect protection against injury from water or from mechanical means.

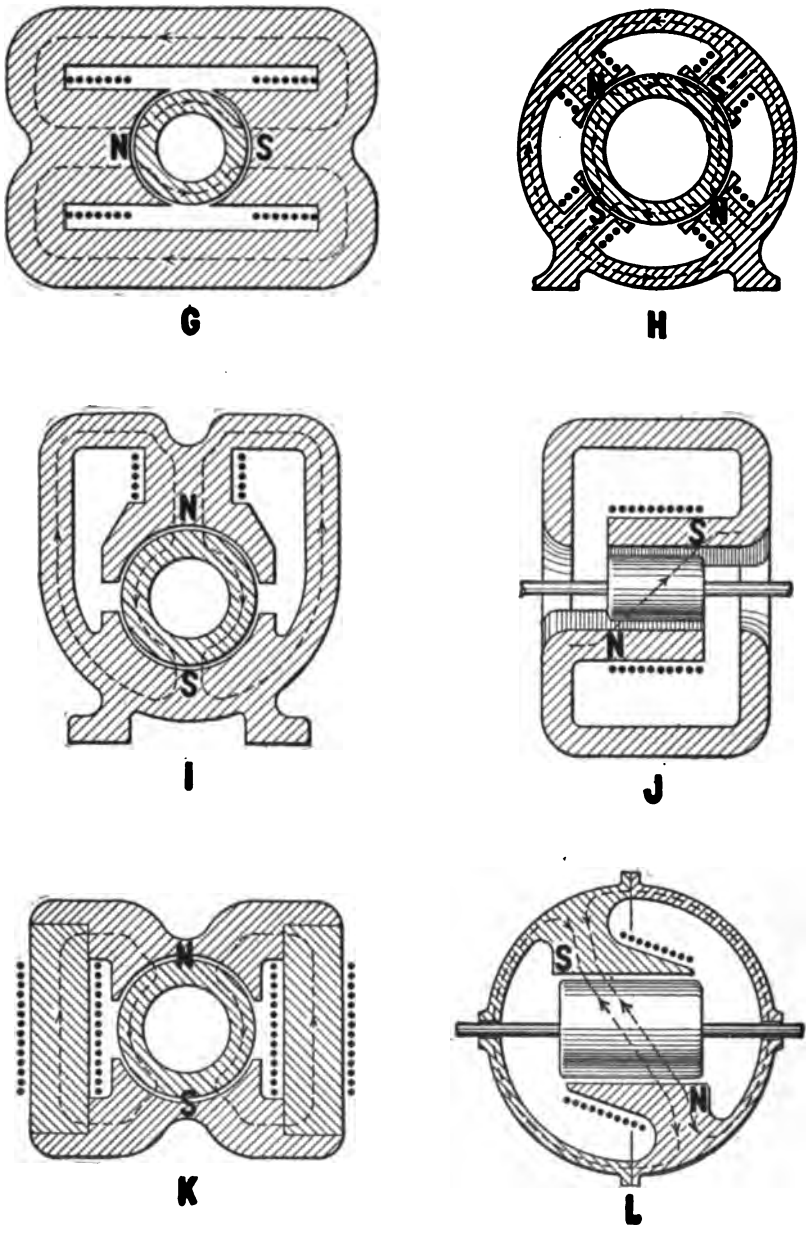


Fig. 16,

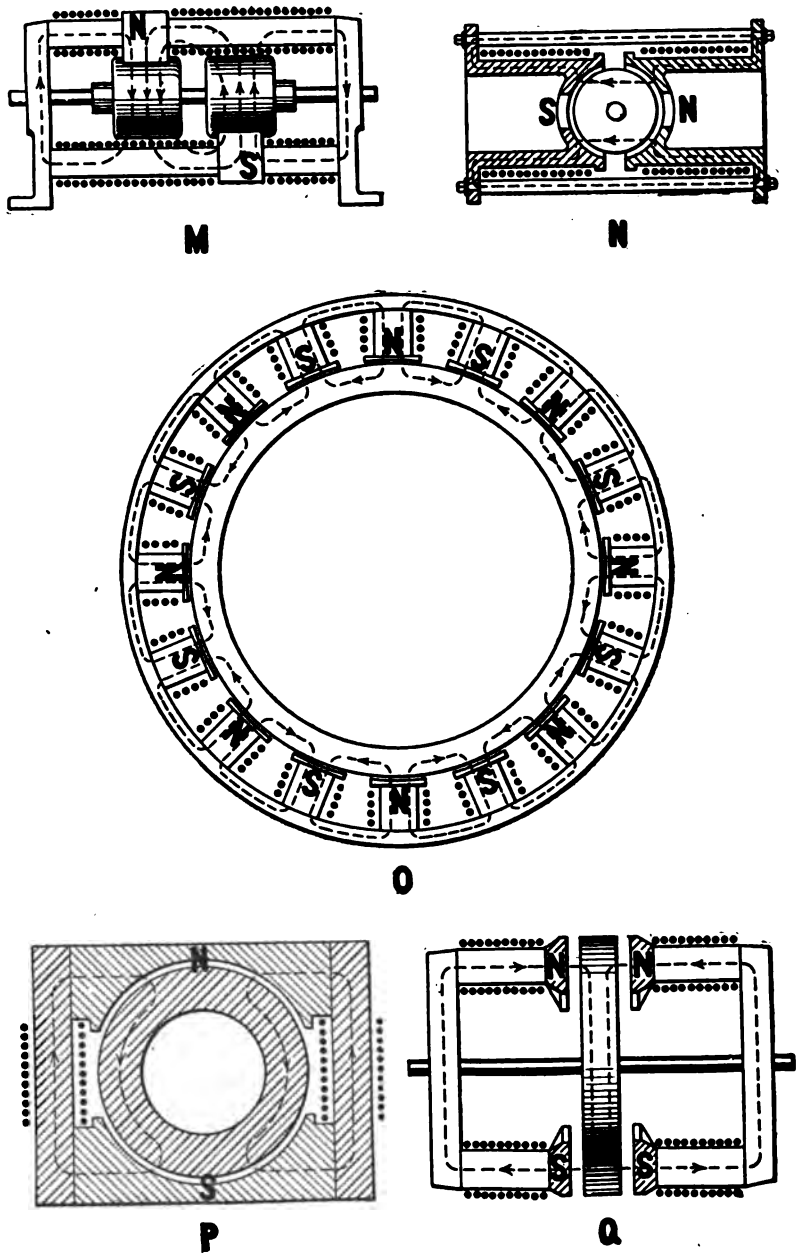


Fig. 17.

A curious modification is the Thomson-Houston "bird cage" arc light machine shown by N Fig. 17. It has tubular magnets and the pole pieces are formed to receive a spherical armature. The return circuit or yoke is made of wrought iron bars. The advantage claimed for this construction is that less wire is needed. Another ingenious form of the ironclad type is that used in the Lundell motor shown in section by L Fig. 16. There is but one coil which encloses the pole pieces, the whole being in turn completely incased by the remainder of the magnetic circuit.

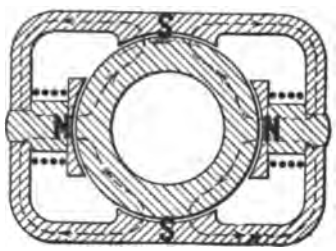


Fig. 18.

The double magnetic circuit type, modified by the formation of a pair of extra poles on the pieces which form the return circuit as in Fig. 18, gives rise to the four-pole type and hence to the multipolar multi-circuit type.

The multipolar field magnets are usually circular in form with inwardly projecting pole pieces. Siemens & Halske use a form having outwardly projecting pole pieces with the armature ring rotating outside the field as shown in Fig. 20. This gives a better magnetic circuit but introduces mechanical difficulties in securing armature supports. Sometimes the multipolar field is built with the coils on the yokes between poles instead of on them.

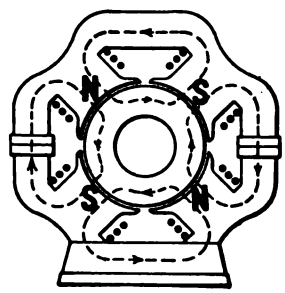


Fig. 19.

The circuit of the Ball dynamo is shown by M Fig. 17, and that of the Brush dynamo by Q. Fig. 19 and H Fig. 16 show magnetic circuits of typical small multipolar dynamos. The magnetic circuit of a large multipolar dynamo with inwardly projecting poles is shown by O, Fig. 17.

For large machines the multipolar type is most in use because it results in a saving of both copper and iron and gives a more symmetrical arrangement. Below 10 K. W. capacity the bipolar forms are to be preferred as they are simpler. The bipolar single circuit types are generally superior to the double circuit types

because they need less wire and are less subject to magnetic leakage.

DYNAMO CONSTRUCTION.

The Armature. The armature of a dynamo is that portion of the machine in which the electrical output is generated. The principle underlying every armature is the law of induction, that any conductor which cuts across a magnetic field has electromotive force generated in it which tends to set up a current. The various armatures of modern commercial machines are the mechanical means which experience has shown to be best adapted to carrying out the law of induction serviceably and efficiently under the various conditions and uses to which the machines are subjected.

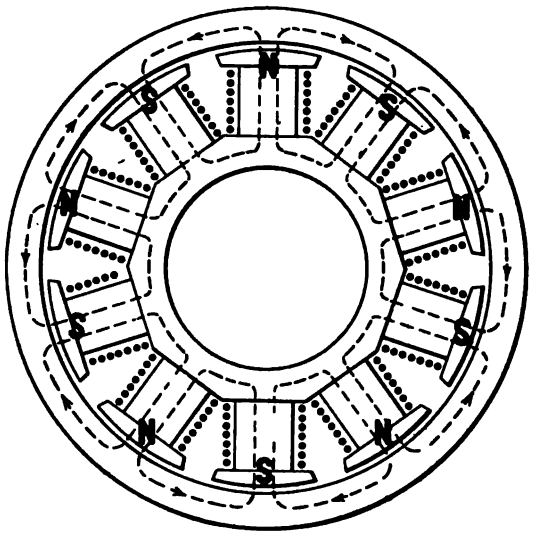


Fig. 20.

The two forms of armature in common use and from which nearly all others have been derived are the Gramme or *ring-wound* armature, and the *drum* or shuttle-wound armature. Fig. 21 shows a diagram of a simple ring armature with one coil, and Fig. 22 a diagram of a drum armature. In practice the number of coils on a single armature is of course large. In the Gramme type the iron core is a ring on which the coils are wound. In the drum type the core is a cylinder, the coils being wound on the surface and ends. Where slow speed is desired the ring armature is most generally used; the ventilation is better and a high insulation is more readily obtained.

There is also the pole armature, with its conductors wound upon iron cores projecting radially outwards; and the disk arma-

ture which has no core, the conductors forming a flat disk which rotates in a narrow gap between the pole pieces.

The Armature Core. The iron armature core not only serves as a support for the armature conductors but also serves as a medium of low reluctance through which the magnetic flux from pole to pole may readily pass.

If the core consisted of one solid piece of metal, it would, since it rotates in a varying magnetic field, have currents induced in it, as is the case in the conductors on its surface. The iron itself would form a closed circuit for these currents, which are known as Foucault or eddy currents. Their presence would not only be a waste of energy, but would also cause injurious heating. These currents are, however, largely reduced by laminating

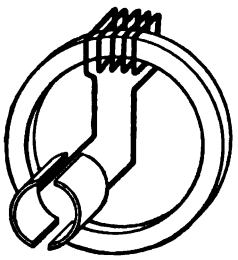


Fig. 21.

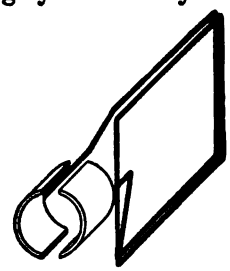


Fig. 22.

the core, that is, by building it up of thin insulated sheets of iron. These sheets or discs are perpendicular to the direction in which the induced currents would flow, and therefore break the otherwise closed circuit. The discs, being perpendicular to the direction of the induced currents are parallel with the lines of magnetic flux and therefore this lamination does not increase the resistance to the magnetic flux. The core of a drum armature is made up of a number of circular discs, and a ring core is made up of a number of similar rings. The discs may be insulated from each other by sheets of paper, a coating of varnish or by rust that is allowed to form on their surface.

The higher the permeability of the material of which the core is composed, the less will be the hysteresis loss and the greater may be the magnetic flux per unit of cross section; the core discs are therefore punched out of the softest sheet iron or soft steel, which in some cases is afterwards annealed.

It has largely become the practice to use **toothed** armature cores shown in Fig 23, the conductors being laid between the teeth and within the outside surface of the core. The air-gap between the core and pole pieces can then be reduced to a minimum, and the conductors are well protected from injury. The conductors are also securely held in place. Such cores are, however, more expensive to make and unless proper precautions are taken, the teeth are likely to set up eddy currents in the pole piece surfaces.

Armature cores are usually built up on an internal frame or skeleton which is in turn firmly keyed to the shaft. In drum armatures the core discs may be keyed directly to the shaft, or the shaft and hole through the discs may be made square or octagonal. The discs are sometimes held together by large nuts screwed directly on the shaft, or, as is usually the case, by bolts passing through the discs. In the latter case end-plates somewhat thicker than the discs are provided, and to reduce the presence of eddy currents which would occur if the plates were of iron, they are sometimes made of brass or other non-magnetic metal. These bolts and end-plates are always insulated from the core by tubes and washers of paper, fiber, or mica.

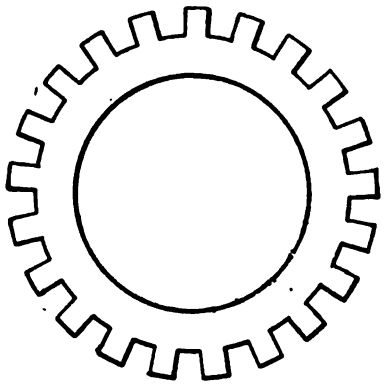


Fig. 23. Toothed Armature Core.

The core of ring and of large drum armatures, being in the form of a ring, must be supported on some form of spider. This consists of a hub or sleeve keyed to the shaft and is provided with projecting arms which support the core. A simple construction is shown in Fig. 24. Two spiders are used, the core being clamped between them. It will be noticed that the bolts do not pass through the core and therefore are not in the path of the magnetic lines.

Before the conductors are applied the core should have all sharp or rough edges removed. In order to secure good insulation from the conductors the cores are covered with a few layers of

insulating material; smooth cores have a continuous layer of insulation over their surfaces, whereas in toothed cores the insulation is applied only in the slots between the teeth.

Armatures of bipolar dynamos usually run at a speed of from 800 to 1,400 revolutions per minute; the armatures of direct connected machines and others which are of the multipolar type sometimes run as slow as 150 per minute, but their diameters may be so large that the peripheral speed is not far from that of a smaller machine. Under these conditions the centrifugal force acting on the conductors is quite appreciable.

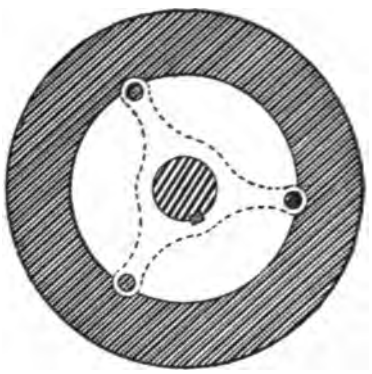


Fig. 24. Shaft and Spider Supporting Armature Core.

There is also another mechanical force to be provided for due to the magnetic pull exerted on the conductors by the field. It is against this pull that the steam engine driving the dynamo does work, and were they not strongly secured the conductors would be stripped from the armature. In order to prevent any motion of the conductors during the operation of an armature, hard brass wire is wrapped around the outside in bands; these are called **binding wires.**

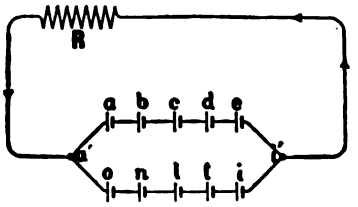


Fig. 25.

On account of the high speed and small clearance in the air-gap, armatures are very carefully *balanced* to prevent injurious vibration. The usual method of doing this is to support the armature and its shaft on two horizontal, wedge-shaped metal rails called knife edges. The armature is then given a turn and it is noted whether there is any tendency to come to rest with any particular part of the armature downwards. If this is the case, small pieces of lead are inserted on the opposite side until the armature will come to rest in any position.

Armature Windings. The law of induction tells us that a

loop of wire carried through a field in such a manner as to vary continuously the number of lines of force that are included within its boundary will have an E. M. F. generated in it. Two loops connected in series will double the effect, or twice the field strength will also double the effect. Dynamos are designed with this in view, and to produce the desired voltage the coils are made of a certain number of turns and the fields of a certain strength.

There are two general methods of winding armatures giving rise to the terms **closed coil** and **open coil.**

Closed Coil Armatures. The closed coil type of armature is used for constant potential machines, in incandescent lighting and power distribution, and in some cases for constant current machines. The coils are wound continuously around the ring or cylinder as the case may be, the end of one coil being joined to the beginning of the next, and this junction is connected with a segment of the commutator.

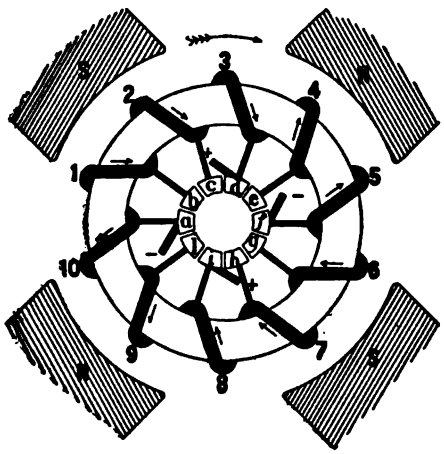


Fig. 26.

Each coil adds its quota to the electromotive force at the brushes, the amount depending at any moment on the position of the coil in the field. As the coils revolve the E. M. F. generated by some coils is increasing, while that generated by others is decreasing; but the sum total between the brushes remains the same, for the loss in effectiveness of one coil is balanced by the gain in another. The effect of the coils in a closed circuit winding is sometimes compared to a set of voltaic cells, one in each coil, as shown in Fig. 25. This would, however, be a more accurate illustration if the voltage of the cells were of varying strength according to their position in the chain. When two brushes are used there are two paths for the current from one brush to the other through the armature, and the resistance of the armature is then $\frac{1}{4}$ the resistance of the total amount of wire upon it, for the

total length of wire is halved and the halves are connected in parallel.

There have been many variations in winding, all based on the drum or ring winding, and resulting from the necessity of reducing the cost of manufacture and from the increase in the number of poles used in a single machine. The armatures of small machines are usually wound with copper wire, which in larger machines is replaced by copper bars, these bars being laminated above certain sizes to prevent the occurrence of eddy currents in their own mass.

The use of more than two poles greatly increases the variation which it is possible to make in the windings. Fig. 26 illustrates the winding and connections of a four-pole ring armature. As there are four neutral points it is necessary to use four brushes, two positive and two negative, the winding forming a closed circuit from brush to brush. To supply the external circuit the two positive brushes are connected giving one positive terminal, and the two negative brushes are connected giving one negative terminal. Thus the external current in passing through the machine subdivides at the two brushes and again subdivides in the armature, therefore only $\frac{1}{4}$ of the total current passes through each conductor. The internal resistance is $\frac{1}{16}$ of that of all the wire on the armature. Similarly more poles would cause the current to divide a greater number of times.

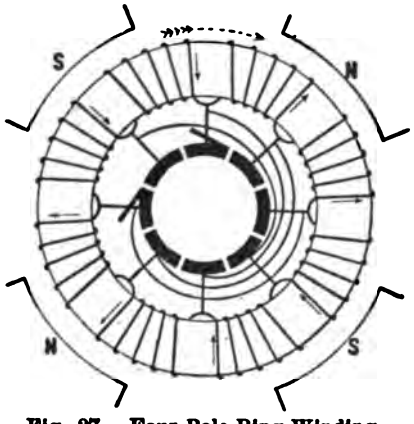


Fig. 27. Four-Pole Ring Winding.

It is not always necessary to have as many brushes as there are neutral points or poles, although this is usually the case. By the simple device of **cross-connecting**, a diagram of which is shown in Fig. 27, the number of brushes may be reduced to two. Each coil is cross-connected with others occupying a similar position under the corresponding pole. This cross-connection may be either in the armature itself or in the commutator.

A method by which armature windings and connections are clearly shown consists in laying the poles and winding out in a plane surface, or in showing the winding as it will appear when

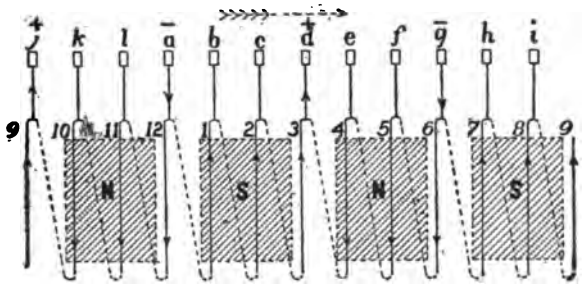


Fig. 28. Developed Ring Winding.

unfolded upon a plane surface. Such a development of the winding of a ring armature is shown in Fig. 28. Figs. 29 and 30 show two windings called the **lap** and the **wave winding** respectively. They are more like the drum winding than the ring, being entirely exterior to the core. A portion called an *element* is shown heavier than the remainder of the windings which are all similar to it.

A conductor on a revolving armature generates an E. M. F. under a north pole in the opposite direction to one under a south

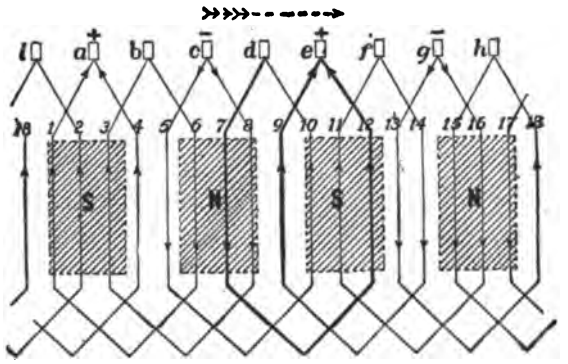


Fig. 29. Developed Lap Winding.

pole, so that it is possible to lay out a wire on the surface of an armature, carrying it across the ends from point to point, in such a way that it will be subjected to an inductive effect tending to

drive the current in the same direction throughout its length. The two ways of obtaining this result are illustrated in Figs. 29 and 30. The reason for calling them *lap* and *wave* windings is that one doubles back on itself every turn, while the other goes ahead in a continuous zig-zag, as will become apparent by following an element.

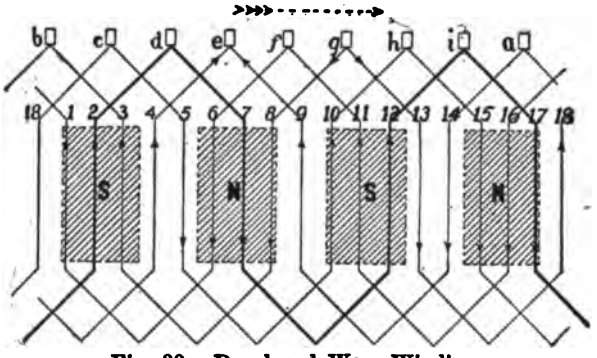


Fig. 30. Developed Wave Winding.

Open Coil Armatures. In the open coil type of armature, which is used chiefly for arc lighting or constant current machines, the various coils, which are few in number, are not interconnected; each winding performs its function independently of the others, and is cut into the circuit by the commutator at the time of greatest activity and is entirely disconnected from the circuit when it is idle.

The commutators of such machines are made up of few segments which are insulated from each other by air spaces. These machines generally spark considerably at the brushes on account of the actual break in the circuit of the separate armature coils.

Fig. 31 shows a diagram of a Brush arc machine which is ring-wound. There are four coils, the two coils *A* and *C* of one winding being in series and terminating in a two part commutator, while the others *B* and *D*, also in series, terminate in another two part commutator. The commutators are placed side by side and the segments are made long enough to overlap so that sometimes the brushes are connected to one pair of terminals, sometimes to the other, and sometimes to both at once. When the brushes *E E* touch both sets of terminals at once thus bringing the two wind-

ings in parallel, a current would be set up in one winding by the other owing to the difference in activity of the two, were it not for the high self-induction of the coils. The contact between the brushes and a pair of terminals breaks just when the coils connected have reached the point of least activity. The completed

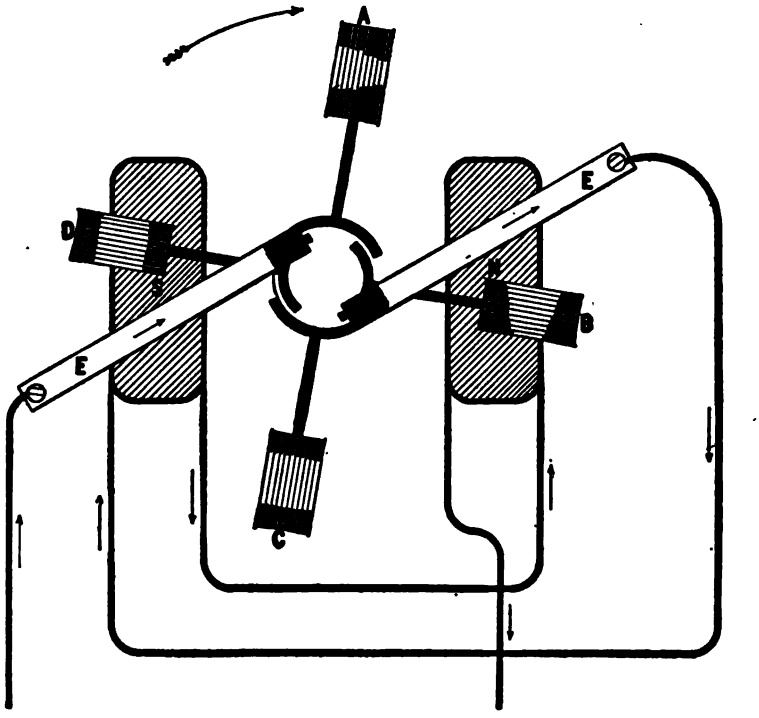


Fig. 31. Diagram of Brush Arc Dynamo.

dynamo has another set of coils between those shown, on the same ring, and another commutator and pair of brushes beside the first set. One brush of the first set is connected to the outside circuit, the other is connected to one of the brushes of the second set while the remaining brush is connected to the other terminal of the outside circuit through the field coils. In this way the two sets of windings are brought in series with each other and owing to their relative positions, one is at a maximum activity when the other is at a minimum, one increases as the other decreases, and *vice versa*, so that the sum total of the action tends to keep the current from fluctuating.

Commutators. It has been shown how current generated in a coil revolving in a magnetic field is necessarily alternating, being generated in one direction through the coil when the coil is rising through the field and in the opposite direction when it is descending. The first machines built were alternating current machines, but as the alternating current could then only be used for a few purposes the invention of the commutator soon followed. The simplest form of dynamo is a single coil revolving in a field, the terminals of the coil ending in two pieces of metal which form the halves of a circle, and with which the brushes are in contact. As the coil rotates, first one terminal and then the other comes

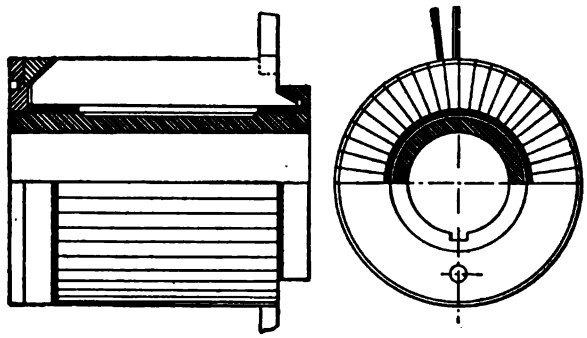


Fig. 32. Commutator.

under a brush. If the brushes are put in the right place the terminals will always have the same polarity when they make contact with the brushes so that a continuous current can be drawn from them. The current is continuous however, only as regards direction for the strength of the current is varying.

As the coil moves into the denser part of the field the current increases, and as the coil moves out the current decreases. If we had two coils at right angles to each other, moving through the field in the same time, the pulsation would only be half as great as with one. We can therefore make the pulsation as small as we like by increasing the number of coils and hence the number of commutator segments. The fluctuations become perceptible in a two pole machine when less than 30 coils are used; and the commutator bars seldom exceed 100 for this type of machine on account of increased expense. In larger machines the

total number of commutator segments increases with the number of pairs of poles.

The commutator must be well designed mechanically as well as electrically. Each segment must be carefully insulated from adjacent ones and from the shaft upon which it is built up. The insulation between the segments consists of sheets of mica which have been selected for firmness, freedom from cracks, and uniformity in thickness. The segments taper toward the center so that they will build up into a cylinder. The whole is firmly clamped together by insulating rings held in place by metal rings and lock nuts. Figs. 32 and 33 show two different methods of securing the

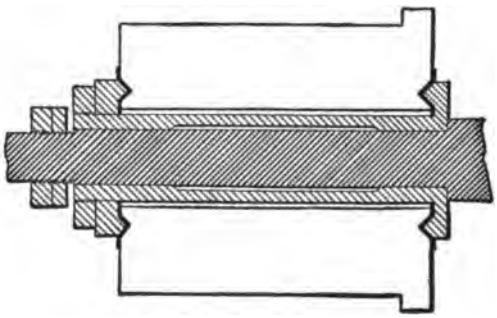


Fig. 33. Commutator.

assembled commutator bars. The best material for the commutator bars is hard copper or silicon bronze which should be as nearly pure as possible and uniform in its structure. The commutator is designed larger than necessary so as to allow for the continual wearing away of its surface; and also to allow it to be turned down from time to time when the surface becomes rough as the result of uneven wear or accident.

Brushes. The cross section of the brush must always be large enough to carry the maximum current which it is likely to be called upon to furnish, with a liberal factor of safety. The thickness at the contact with the commutator should not be less than one and a half times the insulation between the bars and is usually greater. The material must be softer than that of the commutator so as to wear the brush rather than the commutator.

There is a large number of different forms of brushes, each having its special advantages and disadvantages. In the Brush

arc dynamo the brush consists of a simple strip of sheet copper having slits in it to insure good contact, and is set almost tangent to the commutator.

The wire brush has been much used and is still employed; it consists of a bundle of fine copper wires all soldered together at the end furthest from the commutator, and being inclined to its surface, the brush has the contact end beveled to fit the commutator in order that the ends of all the wires may make contact.

Copper gauze brushes consist of sheets of fine copper gauze folded or rolled up and pressed into rectangular form. These brushes owing to their soft spongy nature secure excellent contact with the commutator.

The carbon brush is now used more than any other. It is usually applied radially giving the advantage that if the machine is run backwards, through accident or intention, there is no danger of ruining the brush by causing it to trip on the edge of some commutator bar that might be slightly out of place. It also wears a better surface on the commutator and the amount of wear is much reduced. The collection of carbon dust is far less objectionable about a commutator than that of copper dust being less likely to cause a short circuit. The main advantage of the carbon brush is the reduction of sparking. As carbon has a high specific resistance it tends to keep the current down when the commutator bars are short circuited by coming under the brush, and there is therefore little or no sparking when a bar breaks contact with the brush. This advantage becomes less marked in machines having many segments in the commutator and very low difference of potential between them, for in such machines there would be little sparking even with copper brushes having high conductivity.

Brush-Holders. The brush must be held rigidly in position by a mechanism called the **brush-holder** which is capable of being revolved part way around the shaft so as to shift the point of contact between the brush and the commutator. The holder is usually mounted on a collar which in turn is mounted on a hub formed by a projection from the journal box. An insulated handle is provided by which to shift the brushes to the desired position, and it is often made to screw into the collar in such a way that the brush-holder can be locked in any position. In very

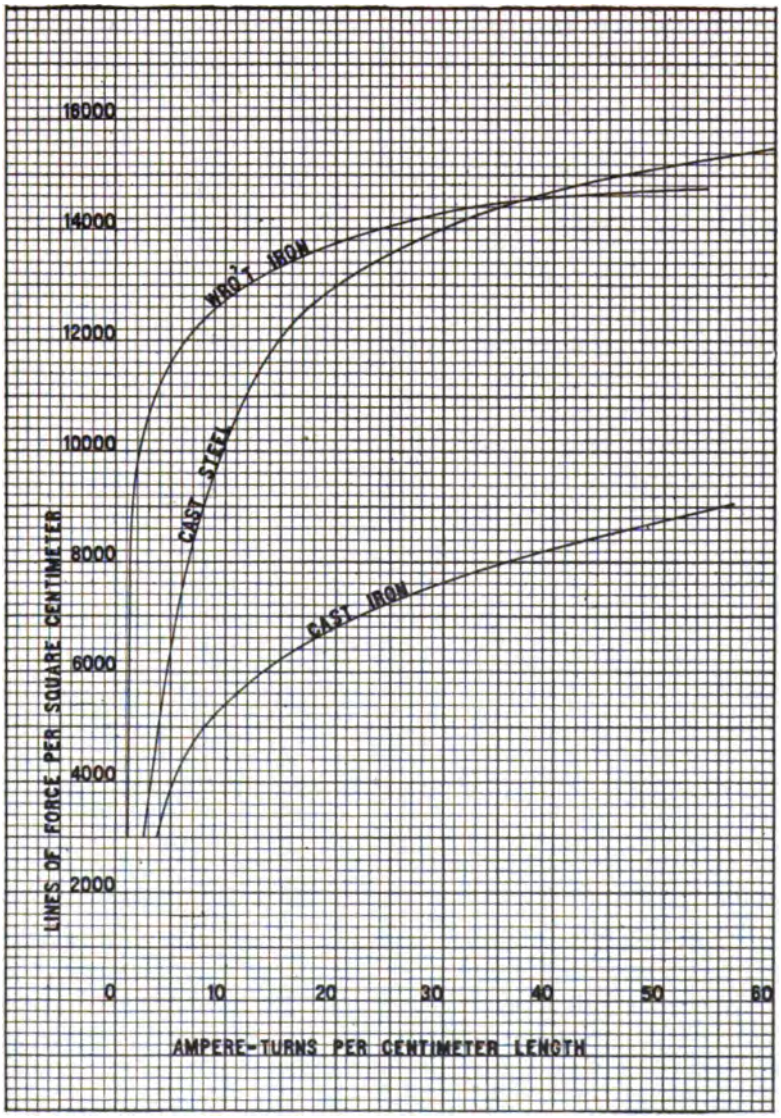


Fig. 34. Curves of Magnetic Induction.

large multipolar machines where there are as many brushes as poles, a substantial ring is formed separate from the machine. This ring is supported from the field casting by arms, and is shifted by the aid of a hand wheel and worm meshing with teeth on the ring.

Except in very small machines brushes are subdivided into two or more parts pivoted on the same shaft of the brush-holder. By this means of construction one brush at a time may be lifted and examined without breaking the circuit or interfering with the operation of the machine. The brush-holders are generally provided with adjustable springs which give the brushes a proper pressure on the commutator. If much of the current is allowed to pass through the springs, they are heated and soon lose their temper, and they cannot then exert sufficient pressure on the brush. The springs are therefore insulated, or arranged so that only a very small part of the current passes through them.

Field Magnets. In the construction of the field magnets the principal materials used are cast iron, cast steel, and wrought iron. Usually a combination of two of these is used. In Fig. 34 are shown curves of magnetic induction for cast iron, wrought iron and cast steel.

Cast iron has the lowest permeability of the three and hence for a certain magnetic flux must necessarily have a larger cross section. It is customary to allow a density of about 45,000 lines per square inch for cast iron. This material is used, on account of its cheapness, for yokes, polepieces, bases, or in general where extra weight or size is not objectionable. This extra weight is often an advantage since it gives greater firmness and stability.

Wrought iron is generally considered to have the highest permeability of any material and a density of about 90,000 lines per square inch is usually allowed. Owing to its high permeability, wrought iron is used where a small cross section is desirable, and this is especially the case in field cores. To wind a certain number of turns upon a wrought-iron core will require a considerable less length of wire than if a core of some other material large enough to carry the same magnetic flux were used. If a cast-iron core were used the length of wire would be about 1.5 times that needed for a wrought-iron core for a given number of turns.

The improved and cheaper processes of casting soft steel having a low percentage of carbon, has led to its adoption for field magnets in many dynamos. Cast steel has a very high permeability and some varieties have a higher permeability than that of wrought iron; it is customary however to allow a density of about 80,000 or 85,000 lines per square inch. Cast steel is always used for field magnets where lightness and small size are desirable.

Field Coils. For convenience in construction and repair of field coils they are usually wound on a separate form and then placed in position on the cores. The cylindrical form upon which they are wound often consists of tubes of brass or tin, having flanged ends. The coil should be insulated from this tube by a few layers of thick paper or fibre. The finished winding should be perfectly symmetrical or as nearly so as possible. The leads from the coil should be carefully protected and insulated; this is especially the case with the inner terminal, which is usually carried out through a hole in one end of the tube or spool.

As the conductors of series coils often must be of large size, they are difficult to wind, and therefore usually consist of several smaller wires connected in parallel, or of ribbons or strips of sheet copper. In compound-wound machines the series and shunt windings may be separate or on the same spool. In the latter case the shunt coil and series coils are wound in separate compartments of the spool. When the coils are separate there is the advantage of greater ease in repair and also greater radiating surface.

SPARKING.

It sometimes happens that heavy sparking takes place at the brushes of a dynamo and if this is not prevented it soon burns and roughens the surface of the commutator and the brush so badly that the dynamo is thrown out of service. Sparking may result from either mechanical or electrical faults. If one bar of the commutator is higher or lower than the rest there will be a spark every time it passes under the brush, or if the lead from an armature coil to one of the commutator bars should become disconnected, or if there should be a break in some other part of the

coil, there will be flashing when the bar passes under a brush. If the sparking is continuous and not due to mechanical causes the brushes should be rocked one way or the other until a position is found where the machine runs sparklessly, or nearly so.

When a dynamo is in operation the current passes from the positive brushes through the external circuit to the negative brushes, and then sub-divides and passes through the armature to the positive brushes. To understand the production of sparking due to an incorrect position of the brushes it is necessary to consider the commutation at one brush only.

Referring to Fig. 35 , it is evident that the current passes through coils 2 and 3 to segment *d* in one direction and through coils 5 and 4 to segment *d* in the opposite direction. From segment *d* the current passes to the positive brush and to the external circuit. Further movement of the armature in the direction of rotation will bring both segments *c* and *d* under the positive brush at the same time and coil 3 will then be short circuited.

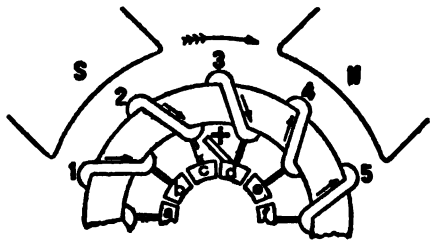


Fig. 35

That is, these two segments, the brush and coil 3 will form a complete circuit of very low resistance, and the current may pass from coil 2 directly to segment *c* and the brush, and from coil 4 directly to segment *d* and the brush. As the armature continues to rotate, coil 3 will come under the north pole and segment *c* under the positive brush. The current must then pass from coil 4 through coil 3 to segment c and the brush. In passing the brush coil 3 is therefore at first short circuited and afterwards is traversed by a current in the reverse direction to that originally considered. Each coil successively passes through the same positions. Now, supppose the position of the positive brush is such that when coil 3 is short circuited it is cutting no lines of force and therefore generating no E. M. F. Then there will be no current and as the coil passes to the right it will be perfectly idle, and when segment *d* leaves the brush the large current from coil 4 should pass through coil 3 to get to segment *c* and the brush. On account of

the large self-induction of the coils, however, the current cannot immediately rise to its full value in coil 3 and hence will prefer to jump from segment *d* to *c*, causing sparking. Now consider the result when the brush is shifted to the left or backwards, so that when the coil is short circuited it is still cutting lines of force. The generation of a slight E. M. F. will cause a large current to flow on account of the very low resistance of the coil, and the direction of this current will be opposite to that which the coil must next convey. For such a position of the brush excessive sparking will result.

Now consider the brush to be moved forward or to the right, so that while the coil is short circuited it is passing into the field at the right or under the north pole. The E. M. F. generated by coil 3 will then cause a current to flow which will be in the same direction as that in coil 4, and when segment *d* passes from under the brush the current in 3 already has a certain value. The correct forward position of the brush is such that coil 3 generates just sufficient E. M. F. to produce a current equal to that which passes in coil 4. No sparking will occur under these conditions, as the effect of self-induction has been counteracted and the current from coil 4 will readily pass to 3. If the brush is too far forward, too large a current will be generated, and cause sparking. The brush must be set forward a greater amount for large armature currents, since the short-circuited coil must generate a higher E. M. F. to produce the large current. The distortion of the field by the armature also necessitates the shifting of the brushes forward.

INSTALLATION AND OPERATION.

A good foundation is the first requisite in a dynamo installation. With belted machines the high speed may give trouble if the foundation is insecure. With direct driven machines the engine and dynamo should be mounted on the same bed plate if the size permits. In selecting a position for the dynamo, freedom from dampness and dust should be secured and also good ventilation. A belted dynamo should be far enough away from its driving pulley to allow the belt to have good contact. A modern direct connected unit of 25 K. W. capacity is shown in Fig. 86.

Most machines of modern design are furnished with self-aligning and self-oiling bearings. If there are a number of machines in one installation each of which is fitted with oil cups, it may be advisable to have a system of oil pipes arranged to dis-

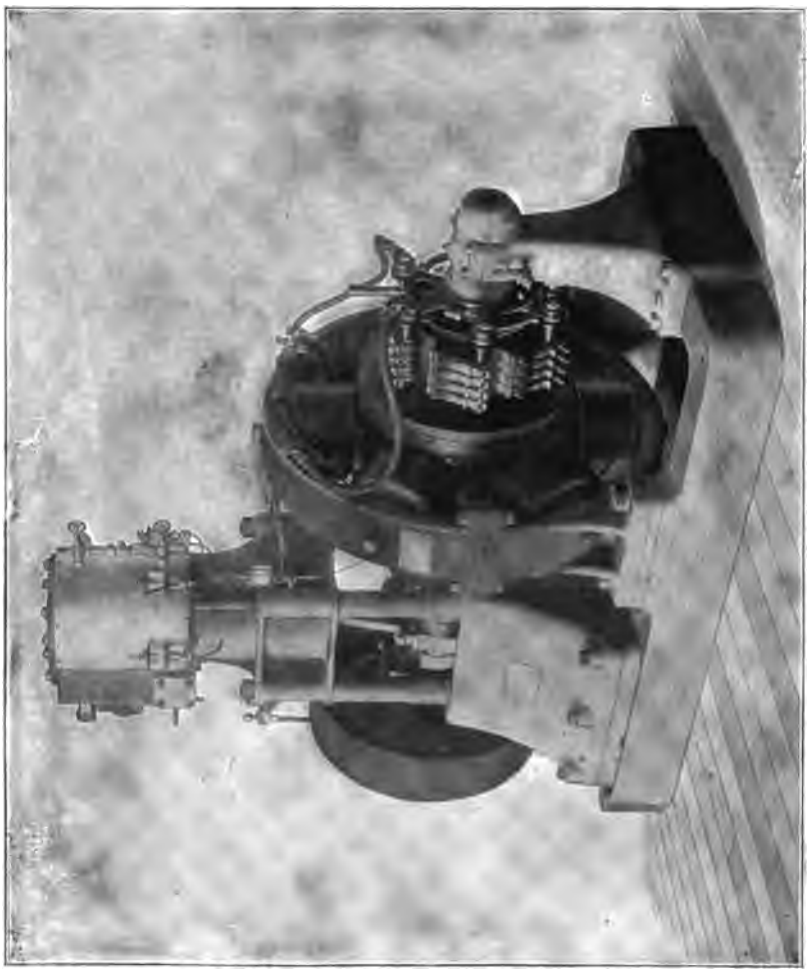


Fig. 36. General Electric Direct Connected Generating Set

charge oil through a stop cock into the oil cups. All oil cans should be of non-magnetic material, to prevent accidents which might arise from the attraction that would be exercised on an iron can when placed near some parts of the dynamo.

All electrical machinery should he kept scrupulously clean

Brushes should at all times be kept in good contact with the commutator, with their faces properly bevelled, and if they are of metal, the armature should never be allowed to run backwards. The commutator must be kept smooth and polished, as any roughness will cause sparking and a burning of the surface. If each brush-holder supports two or more brushes as is generally the case, they should be staggered enough to prevent uneven wearing of the commutator. The commutator is the most delicate part of a dynamo and consequently requires special care. Commutators should be kept free from oil, as it will carbonize and cause flashing and may even partially short circuit the bars. Where carbon brushes are used the carbon dust should be wiped off from time to time. Some lubricant is generally necessary for the commutator, and it may be applied by holding against it a coarse cloth folded smoothly and containing the lubricant. Vaseline is generally used.

The position of the brushes should be such that the machine runs sparklessly and when a change of load causes sparking the brushes should be shifted at once to the right position, as the commutator will become so badly roughened if allowed to run long in this condition, that it will have to be turned down with a cutting tool. The term *sparkless* means that there are no sparks present sufficiently large to burn the metal. When a machine is running it is possible by looking tangentially to the commutator at the brush to see a line of these blue sparks under the brush.

Dynamos as a rule are not liable to many mishaps if they are properly built and if they receive proper care, but it is often difficult to locate certain faults. A new machine will sometimes refuse to generate when first started; this is often due to entire absence of residual magnetism, making it impossible for the machine to build up. This may be remedied by exciting the field from an outside source, either another machine or a battery. It is however more likely to be due to some bad connection, such as would be produced by getting varnish under a terminal washer or by a loose wire. Sometimes the terminals of the field coils are reversed so that they oppose each other, or perhaps the brushes do not make sufficiently good contact. A shunt machine will not build up if its terminals are short circuited.

Burn-outs in the armature are sometimes produced by exces-

sive heating resulting from overload. A short circuit will very often throw the belt or stop the engine so quickly that there is not time for the armature conductors to melt. Continued overloads not great enough to throw the belt may char the insulation until two conductors lying side by side and differing from each other in potential, come into contact. Vibration due to a badly balanced armature or to an insecure foundation may produce the same trouble by causing abrasion of the insulation on the conductors, so that they touch each other or are both touching the iron core. Dirt between two adjacent commutator bars, due to the collection of copper and carbon dust, may short circuit the coil having terminals in these bars sufficiently to cause it to burn out. Sometimes the connecting pieces between the armature coils and the commutator segments become broken which unbalances the

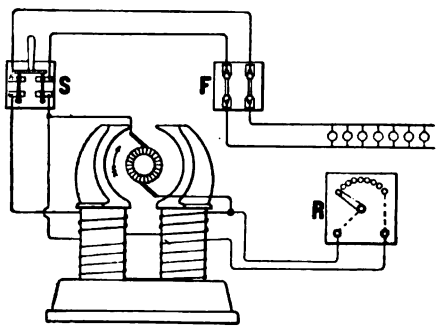


Fig. 37. Diagram of Connections of a Compound-Wound Dynamo.

armature electrically, and causes sparking at the dead commutator bar.

The connection between a dynamo and its outside circuit should always be made through a double-pole switch which cuts both terminals from the circuit. A diagram of the necessary connections and wiring of a compound-wound dynamo is shown in Fig. 37. The leads from the external circuit are first connected to the fuses *F* in order to protect the dynamo from large or dangerous currents. If a current greater than a safe one for the dynamo passes through these fuses they melt and so break the circuit. From the fuses leads connect with the main switch *S*, and from this to the brushes through the series coils. The rheostat *R* is connected in series with the shunt coils for the pur-

pose of regulating the field strength and hence the voltage of the machine. By moving the arm of the rheostat, more or less resistance is inserted or cut out from the circuit and therefore the current in the field coils is varied.

In most stations supplying electrical energy it is not desirable to have a single machine capable of taking the whole load of the station, for at low loads the efficiency would be small. It is therefore desirable to have several smaller machines, so that as the load of the station increases they can be successively added, and so always operated at full load when they are most efficient. The several machines are then connected in parallel between the bus bars from which the external circuits lead.

With shunt machines no trouble is experienced when several are running in parallel. Care must be taken before connecting a new machine to the circuit that it is built up to the same voltage as that carried on the bus bars, for if it is lower the higher voltage will send a current to the machine of lower voltage and drive it as a motor.

With series or compound machines the case is somewhat different. A conductor called an equalizer must connect together all the brushes from which the series coils start. Otherwise any tendency in one machine to raise its potential above that of the others would cause increased potential at the brushes and hence an increased current through the shunt coils, which would still further raise the potential; and if the potential became high enough it would reverse all the other machines on the circuit. This action is entirely obviated by the use of the equalizer, for if the potential of any machine should tend to rise it would drive some of its current across the equalizer connection and through the series coils of the other machines thus raising their potential with its own. Machines differing widely in size can be run together in this way if all are wound for the same potential.

TESTING.

When machinery has been installed it is customary to subject it to certain tests to determine whether or not it fulfills all the requirements. No test can be applied to determine the life of the machine. The life depends upon the general design, material of which it is made,

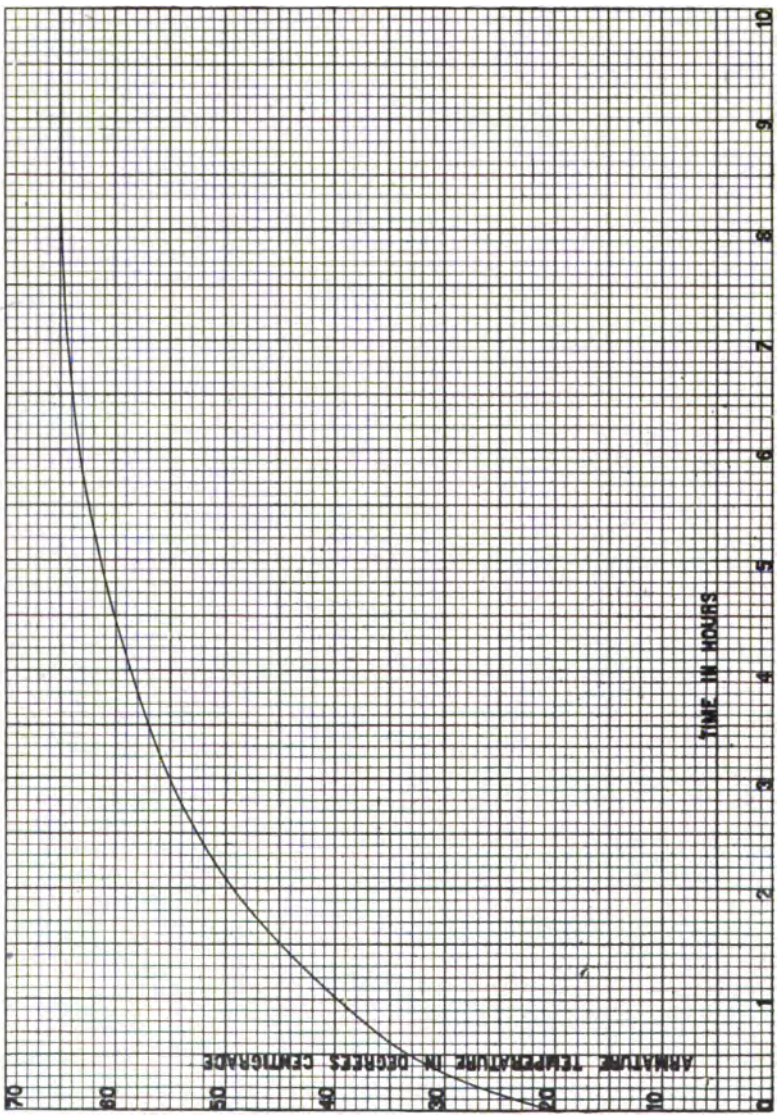
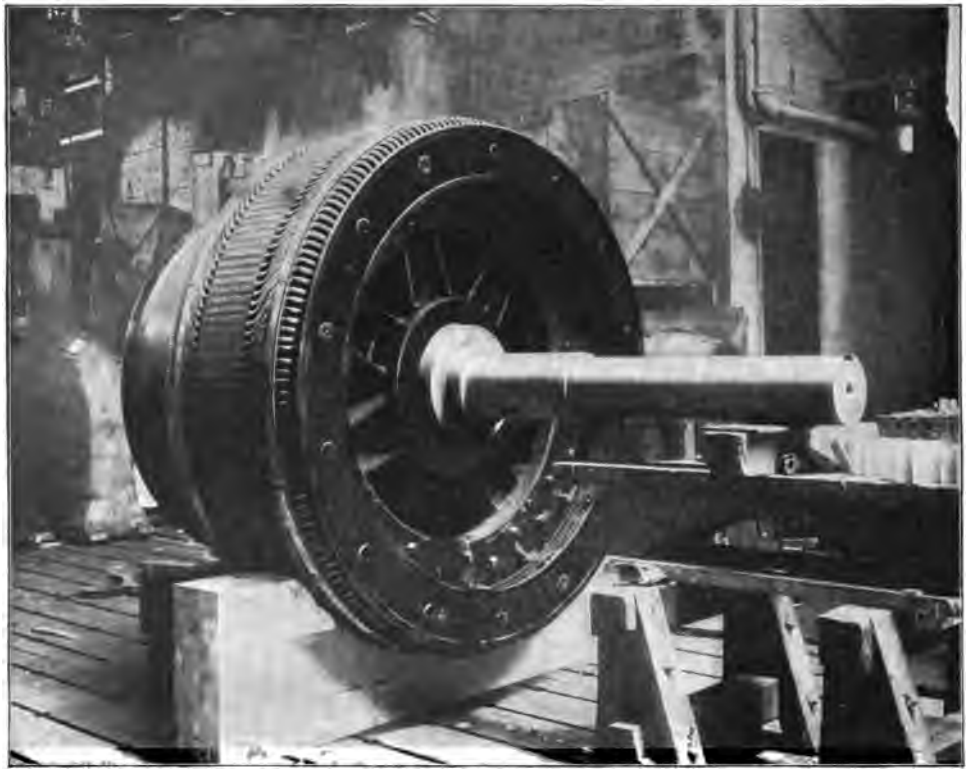


Fig. 38. Rise in Temperature of an Armature of a Large Machine.



ARMATURE OF A 400 K. W., 125 VOLT, TYPE L, WESTERN ELECTRIC GENERATOR.

care used in its construction, and the care it receives during its operation. Only previous experience with similar machinery is of any value as a guide in this respect.

With proper care and good materials the only defect that is likely to shorten the life of the dynamo is overheating. It is customary to specify that a machine shall be so designed that it may run continuously at full load with a rise of temperature in the armature conductors not exceeding 50° C. above the surrounding air. The commutator may be allowed to reach a slightly higher temperature, say 5° or 10° greater. The effect of overheating is to gradually char and weaken the insulation. This test is easily made after the dynamo has been in operation for a few hours at full load by placing thermometers in the armature windings at the back and front where the windings are accessible and allowing them to remain there about ten minutes covered with waste. In general the above requirement is well within the limits of safety. Fig. 38 is a curve of the rise in temperature of an armature when in operation.

In electric light supply it is very essential that the voltage at the lamps should remain at its proper value. If it is too high the lamps will be unpleasantly bright and their life will be much shortened; if too low the lamps will burn too dimly. If short, quick variations occur, even though very small the effect will be noticed in the lamps as flickering. Hence, it is desirable that the engine driving the dynamo should regulate its speed with extreme closeness. Flickering is avoided by the use of a sufficiently heavy fly-wheel, whose proportion will depend on the speed, point of cut off, and length of stroke. It is usual to specify that the variation in speed of the combination of engine and dynamo from no load to full load shall not exceed 3%, and the change in speed during each stroke of the engine must not exceed one per cent so that flickering in the lamps will not be noticeable.

A characteristic curve should always be taken as well as a speed curve, and if the machine is over-compounded to keep the voltage constant at some particular point on the feeder system, a curve for this point should be constructed by subtracting the volts lost in the mains from the external characteristic curve.

Multipolar machines can be built to run sparklessly under sud-

den variations in load as great as from no load to full load, and tests should be made by repeatedly throwing on and off certain proportions of the load, and noting the amount of sparking. It is needless to say that under a steady load the machine should run sparklessly. In many machines the position of the brushes depends somewhat on the load and requires shifting with the load.

If an insulation resistance test is made, it should be done when the machine is hot, and a source of electrical energy at considerably higher voltage than that for which the machine is built should be used, generally from 5 to 10 times as great. One pole is applied to the iron core and the other to the armature winding; if the insulation resists this test, no puncture being formed, it is without doubt free from any defect.

The efficiency of any machine is expressed by the ratio of the energy that it gives out, or output, to that which is supplied to the machine or input. This ratio multiplied by 100 gives the percentage efficiency. If the efficiency of a dynamo is 85 %, then 85 % of the mechanical energy supplied to the machine at the pulley, will reappear as available electrical energy at the terminals, while 15 % is lost. The losses are both mechanical and electrical. The mechanical losses are simply the result of friction in the bearings and brushes besides air friction due to the revolving armature. The electrical losses are due to the resistance of the armature and fields, being equal to the square of the current multiplied by the resistance. There are also additional electrical losses from eddy currents and hysteresis.

To determine the total or commercial efficiency there are several methods, mechanical and electrical, in use. If the machine is run from a belt and shaft a dynamometer can be used. There are many different forms of these machines in existence, the principle underlying them being to pass the pull of the driving power through some form of spring which is bent proportionately, the amount of the force exerted being indicated by a pointer on a scale which can be graduated to read in pounds pull. Knowing the pull applied at the circumference of the dynamo pulley, its radius, and the number of revolutions per minute, the horse-power supplied to the dynamo is found by the formula

$$\text{H. P.} = \frac{2\,\pi\,n\,F\,r}{33{,}000},$$

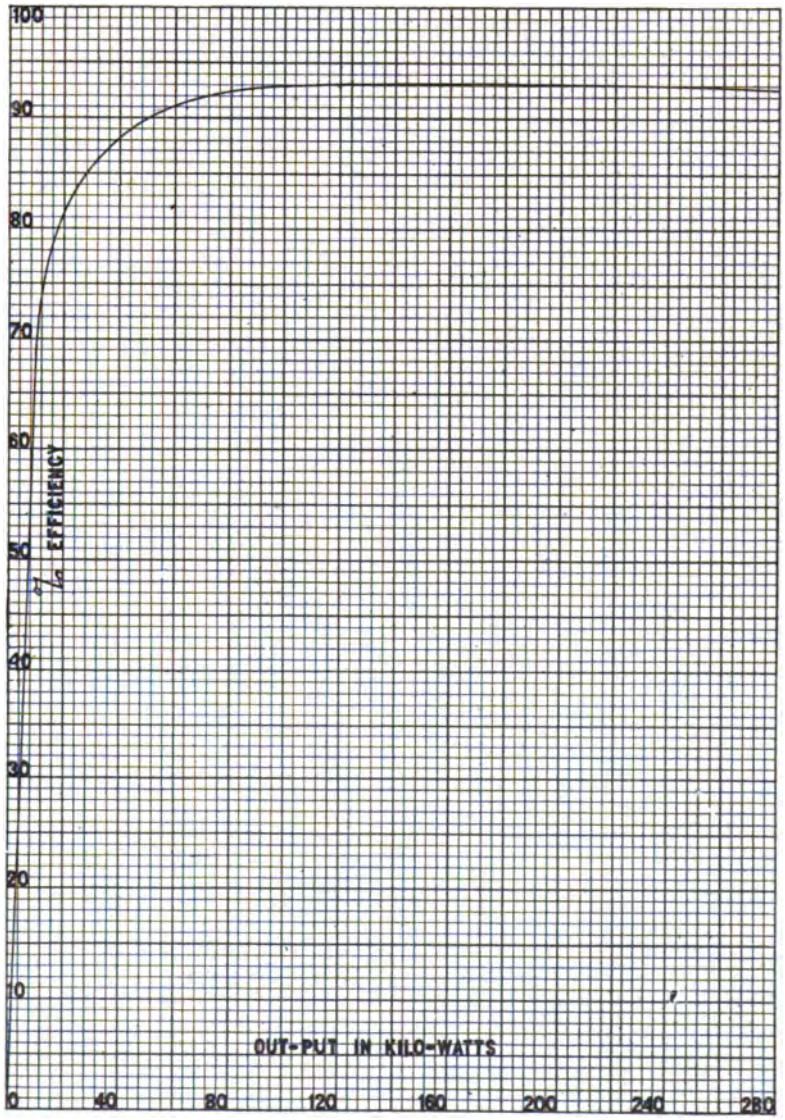


Fig. 39. Efficiency Curve of 200 K. W. Dynamo.

where n is the number of revolutions per minute, F the pull in pounds at the circumference, and r the radius of the pulley in feet.

Knowing the horse-power supplied and the horse-power taken out as given by the product of the current times the terminal voltage divided by 746, the commercial efficiency of the machine in per cent is obtained by multiplying the ratio of the latter result to the former by 100.

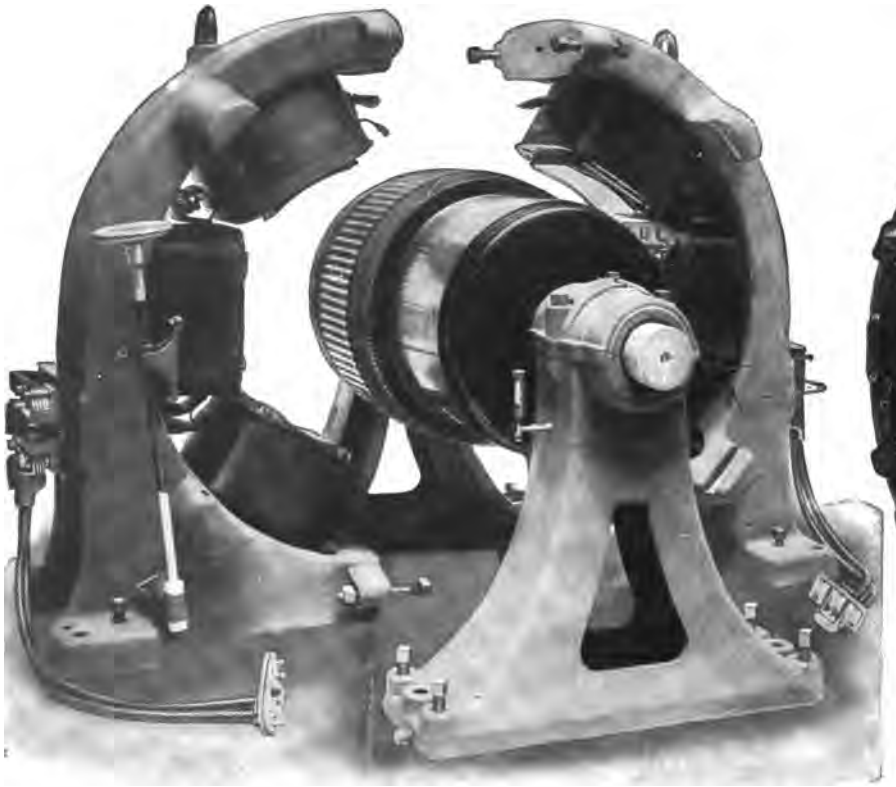
The efficiency is of course very much lower at light loads than at full load because friction is practically a constant quantity for a machine running at constant speed, so that the energy consumed by it bears a much greater proportion to the input at low loads than at high.

An efficiency curve of a Crocker-Wheeler direct connected multipolar 200 K. W. machine for lighting purposes is shown in Fig. 39.

It is not always possible to use a dynamometer, as for instance in the case of a direct connected machine. Under these circumstances the best method is to drive the dynamo as a motor with no load, and note the current required to just keep the machine moving at normal speed. This current multiplied by the voltage at the terminals gives the wasted power. The losses at full load are greater since the current is greater, and the $I^2 R$ losses then have a larger value.

With direct current machinery it is sometimes convenient to take indicator cards on the steam engine from which the steam power developed can be calculated, and at the same time to note the electrical output at the switchboard, the ratio of the two giving the efficiency of the combination. This procedure is only permissible when the load is quite steady; any attempt to do this on a railway generator in service is out of the question, because owing to the fly wheel sudden changes of load are not felt simultaneously in the engine and dynamo. A momentary drop of 30% or 40% in the electrical load would probably not reduce the indicated horse-power in the engine at all for a short space of time; the power thus liberated would go into speeding up the fly wheel.

The best method for obtaining a steady load on a dynamo is to pass the current through a water resistance or rheostat consist-



BRUSH RIGGING.

ASSEMBLING GENERATOR.
(By Courtesy of Western Electric Company.)

ing of a wooden tank filled with water in which hang two iron plates. The terminals of the dynamo are connected with the iron plates, and the resistance and consequently the load is varied as desired by bringing the plates closer together or moving them farther apart. An arrangement which answers the purpose very well can be made from an ordinary barrel with 4 positive plates and 4 negative plates 12″ x 24″ and $\frac{1}{16}$″ thick, held apart by narrow boards 1″ thick placed between them. These boards should be made longer than the plates, so that they can be nailed together above and below. Ordinary furnace grates will also do very well.

Regulation can be secured by suspending the plates by some means above the barrel. They may then be lowered into the barrel to any desired depth. A cold-water supply should be furnished at the bottom of the barrel and an overflow pipe at the top. In this way the water can be carried away as fast as it is heated by the passage of the current. This apparatus will take care of 100 amperes at 550 volts. By adding a handful of salt to the water its capacity can be increased to 300 and even 400 amperes, but at such high values the ebullition is likely to become so great as to be unmanageable.

DYNAMO FORMULAS.

The complete analysis of the dynamo would be out of place here, but several important formulas will be developed to indicate the method.

For the *shunt dynamo* the analysis is as follows:

Let I' = total current in armature;
I_{sh} = current flowing in shunt coils;
I = useful current flowing in outside circuit;
E' = total E. M. F. generated in armature;
E = potential of dynamo, both for shunt coil and outside circuit;
r_a = resistance of armature;
r_{sh} = resistance of shunt field coils;
R = resistance of outside or useful circuit;
η_e = electrical efficiency.

These various quantities can be expressed in terms of each other in a number of different ways. This is of value in studying and understanding the characteristics of the shunt dynamo, and in finding the values of unknown terms when others are known. It is obvious by looking at diagram of Fig. 5 that the total current is the sum of the outside current and shunt current, or

$$I' = I + I_{sh} \text{ or } I' = I + \frac{E}{r_{sh}}$$

This latter equation shows what amount of the armature current is lost in the shunt field. Also the total current in the armature is equal to the total E. M. F. divided by the total resistance,

$$I' = \frac{E'}{r_a + \frac{R \times r_{sh}}{R + r_{sh}}}$$

because the joint resistance of the shunt and outside circuits (see section on the *Electric Current*) is equal to the product of the two divided by the sum of the two.

The relation can be expressed in still another way, since

$\frac{E}{R} = I$ and $\frac{I}{I_{sh}} = \frac{r_{sh}}{R}$ from which $I' = \frac{E}{R}\left\{1 + \frac{R}{r_{sh}}\right\}$

E, R, and r_{sh} are often known quantities from which I' and E' may be found by the aid of these relations. The value of the useful current in the outside circuit is

$$I = \frac{E}{R}$$

and the value of the current in the shunt circuit is

$$I_{sh} = \frac{E}{r_{sh}}.$$

The value of the total E. M. F. generated by the dynamo is

$$E' = E + I' r_a$$

from which it may be seen by inspection that the lost volts in the armature $E' - E$, increase directly with I'. If E' and r_a are considered as remaining constant, then an increase in I' increases $I'r_a$ also, and E must become less. If E is decreased and E' is

constant then their difference which is equal to the lost volts in the armature must increase.

As $I' = I + I_{sh}$, we have by multiplying by r_a and substituting for $I'r_a$ its value $E' - E$,

$$E' = E + Ir_a + I_{sh}r_a = E + \frac{E}{R}r_a + \frac{E}{r_{sh}}r_a$$

$$= E\left\{1 + \frac{r_a}{R} + \frac{r_a}{r_{sh}}\right\} = E \times r_a\left\{\frac{1}{r_a} + \frac{1}{R} + \frac{1}{r_{sh}}\right\}$$

The **electrical efficiency** of the dynamo is equal to the value of the useful energy divided by the total energy developed in the armature, the total energy itself being equal to the useful energy plus the energy lost in the armature, plus the energy lost in the field coils. Therefore the electrical efficiency is

$$\eta_e = \frac{EI}{E'I'} = \frac{I^2R}{I^2R + I'^2r_a + I^2_{sh}r_{sh}}$$

As $I' = I \times \frac{R + r_{sh}}{r_{sh}}$, and $I_{sh} = \frac{IR}{r_{sh}}$ we obtain

$$\eta_e = \frac{I^2R}{I^2R + \left\{I \times \frac{R + r_{sh}}{r_{sh}}\right\}^2 r_a + \left\{\frac{IR}{r_{sh}}\right\}^2 r_{sh}}$$

$$\eta_e = \frac{I^2R}{I^2R + \left\{\frac{I^2R^2 + 2I^2Rr_{sh} + I^2r^2_{sh}}{r^2_{sh}}\right\} r_a + \frac{I^2R^2}{r_{sh}}}$$

$$= \frac{1}{1 + 2\frac{r_a}{r_{sh}} + \frac{r_a}{R} + \frac{(r_a + r_{sh})R}{r^2_{sh}}}$$

By a mathematical analysis it can be proven that the value of η_e is a maximum when

$$R = r_{sh}\sqrt{\frac{r_a}{r_a + r_{sh}}}$$

This equation shows what the resistance of the outside circuit of a dynamo should be, knowing the shunt and armature resistances, in order to have the machine carry the proper load for maximum electrical efficiency.

Replacing R by its value in terms of r_a and r_{sh} we have the terms

$$\frac{R\,(r_{sh}+r_a)}{r^2_{sh}} = \frac{r_{sh}+r_a}{r_{sh}}\sqrt{\frac{r_a}{r_a+r_{sh}}} = \frac{\sqrt{r_a\,(r_{sh}+r_a)}}{r_{sh}}$$

$$\text{and } \frac{r_a}{R} = \frac{r_a}{r_{sh}}\sqrt{\frac{r_a+r_{sh}}{r_a}} = \frac{\sqrt{r_a\,(r_a+r_{sh})}}{r_{sh}}$$

The equation of the maximum efficiency of a shunt dynamo becomes

$$\eta_{e.Max.} = \frac{1}{1+2\,\frac{\sqrt{r_a\,(r_a+r_{sh})}}{r_{sh}}+2\,\frac{r_a}{r_{sh}}}$$

The value of the armature resistance compared with the value of the shunt resistance is always so small that $r_a + r_{sh}$ may be written r_{sh} without any appreciable error and the value of $\frac{r_a}{r_{sh}}$ is so small that it may be neglected, then the approximate value of the electrical efficiency of the shunt dynamo may be written in very simple terms and may be considered as equal to

$$\eta_e = \frac{1}{1+2\sqrt{\frac{r_a}{r_{sh}}}}$$

and the approximate ratio of the shunt resistance to the armature resistance is expressed by the formula

$$\frac{r_{sh}}{r_a} = \left\{\frac{2\,\eta_e}{1-\eta_e}\right\}^2$$

The following table from Wiener gives the necessary ratios of the resistance of the shunt field to the resistance of the armature for various electrical efficiencies for shunt dynamos. As these values are not given in ohms but only as ratios they hold good for all shunt dynamos, large or small. It will be noted that this electrical efficiency may be as near 100% as is desired, from a theoretical standpoint, but the limit is generally governed by the practical consideration of the cost. If the armature resistance is made too small, more copper is used to carry the current than is required, and if the field coil resistance is made extremely high the wire will be very small and very expensive.

TABLE GIVING RATIO OF SHUNT TO ARMATURE RESISTANCE FOR VARIOUS ELECTRICAL EFFICIENCIES FOR SHUNT DYNAMOS.

Electrical Efficiency.	Ratio of Shunt to Armature Resistance.	Electrical Efficiency.	Ratio of Shunt to Armature Resistance.
$100 \times \eta_e$	$\frac{r_{sh}}{r_a}$	$100 \times \eta_e$	$\frac{r_{sh}}{r_a}$
80%	64	96	2,304
85	128	97	4,182
90	324	98	9,604
93	706	99	39,204
95	1,444	99.5	158,404

The *commercial efficiency* is the ratio of the output to the energy supplied; or

$$\text{commercial efficiency} = \frac{\text{useful power}}{\text{total power}} = \frac{EI}{EI + I_{sh}^2 r_{sh} + I'^2 r_a + \text{stray power}}$$

As explained in a previous article, the *stray power* losses are made up of friction, eddy current and hysteresis losses. The stray power can be determined only by testing the dynamo.

In the *series-wound dynamo* there is but one circuit (see Fig. 40), and therefore but one current, I, the value of which

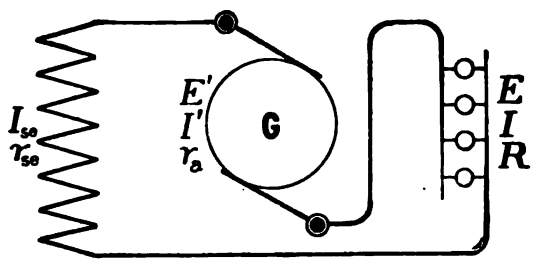


Fig. 40. Diagram of Series-Wound Dynamo.

depends upon the value of the total voltage E' and the total resistance, which is made up of r_a, r_{se} and R. The series field is com-

posed of a comparatively few turns of heavy copper conductor and is connected in series with the armature and the external circuit.

The current may be expressed as

$$I' = I_{se} = I$$

$$I' = \frac{E'}{R + r_a + r_{se}}$$

$$I = \frac{E + (E' - E)}{R + (r_a + r_{se})} = \frac{E}{R} = I'$$

$$I_{se} = \frac{E' - E}{r_{se} + r_a} = I = I'$$

The total voltage may be expressed as

$$E' = E + I(r_a + r_{se}) = E\left\{1 + \frac{r_a + r_{se}}{R}\right\}$$

The electrical efficiency is

$$\eta_e = \frac{\text{useful energy}}{\text{total energy}} = \frac{EI}{E'I'} = \frac{E}{E'}$$

or in terms of resistances it may be expressed as

$$\eta_e = \frac{I^2 R}{I'^2 (R + r_a + r_{se})} = \frac{R}{R + r_a + r_{se}}$$

From the equation $I' = \dfrac{E'}{R + r_a + r_{se}}$ it is seen that an increase in the outside resistance diminishes the current in the field coils, thus diminishing the magnetic flux. As the constancy of the magnetic flux depends upon the constancy of the current value these series-wound dynamos are best adapted to give a constant current, and are used mostly for running arc lamps on series circuits.

From the equation $E' = E + I(r_a + r_{se})$ it is seen that the total current in the armature is the same as the current in the outside circuit, also that the total voltage is the external voltage plus the lost voltage in the armature and series coils due to the passage of the current.

The **Compound-Wound Dynamo** (see diagrams Figs. 9 and 10) may be considered as a shunt dynamo to which some series windings have been added to compensate for the fall in voltage at

the brushes due to the demagnetizing effects of the armature, lost volts in armature, and to compensate for line losses as the load increases. The shunt circuit may either be connected to the brushes, in which case the machine is called the **Ordinary or Short Shunt Compound Dynamo** (see Fig. 9), or the shunt circuit may be connected to the terminals of the outside circuit in which case the machine is called a **Long Shunt Compound Dynamo** (see Fig. 10). Using the symbols as marked on these diagrams the equations for the ordinary or short shunt compound dynamo will be deduced. The total current is

$$I' = I + I_{sh} = I_{se} + I_{sh} = I + \frac{E + Ir_{se}}{r_{sh}}$$

It may also be written (see similar equation on page 66)

$$I' = \frac{E'}{r_a + \frac{(R + r_{se}) \times r_{sh}}{R + r_{se} + r_{sh}}}$$

or again it may be written

$$I' = I\left\{1 + \frac{R + r_{se}}{r_{sh}}\right\} = I \times \frac{r_{sh} + r_{se} + R}{r_{sh}}$$

The value of the shunt current may be written

$$I_{sh} = \frac{E' - I'r_a}{r_{sh}} = \frac{E + Ir_{se}}{r_{sh}} = I \times \frac{r_{se} + R}{r_{sh}}$$

The value of the total E. M. F. generated may be written

$$E' = E + I'r_a + Ir_{se}$$
$$= E + \left\{I + \frac{E + Ir_{se}}{r_{sh}}\right\} r_a + Ir_{se}$$

The value of the total E. M. F. generated may also be expressed in terms of the useful voltage and the various resistances. It is equal to the sum of four lost voltages. The first of these voltages is E, the useful voltage. The next is the voltage lost in the series coil and is equal to $\frac{r_{se}}{R} \times E$.

Then the total voltage at the brushes is

$$E + \frac{r_{se}}{R} E \quad \text{or} \quad E\left\{1 + \frac{r_{se}}{R}\right\} \quad \text{or} \quad E\left\{\frac{R + r_{se}}{R}\right\}$$

The lost voltage in the armature due to that part of the current that flows through the series and outside circuit is to the voltage of the series and outside circuit as the resistance of the armature is to the resistance of the series and outside circuit.

$$\text{Lost volts in armature due to outside current} : E \left\{ \frac{R + r_{se}}{R} \right\} :: r_a : r_{se} + R$$

$$\text{Lost volts in armature due to outside current} = E \left\{ \frac{r_a (R + r_{se})}{R \times (r_{se} + R)} \right\}$$

Similarly the lost voltage in the armature due to the current flowing in shunt field is to the voltage of the shunt field as the resistance of the armature is to the resistance of the shunt field.

$$\text{Lost volts in armature due to shunt current} : E \left\{ \frac{R + r_{se}}{R} \right\} :: r_a : r_{sh}$$

$$\text{Lost volts in armature due to shunt current} = \frac{E (R + r_{se}) r_a}{R \times r_{sh}}$$

Therefore, the total voltage generated being equal to the sum of these four expressions it may be written

$$E' = E + \frac{E r_{se}}{R} + \frac{E (R + r_{se}) r_a}{R (r_{se} + R)} + \frac{r_a (R + r_{se}) E}{r_{sh} \times R}$$

As the third term when simplified has the same denominator as the second term the two may be combined, and as all four terms in the right hand side of the equation contain E it may be taken outside the parenthesis ; then,

$$E' = E \left\{ 1 + \frac{r_{se} + r_a}{R} + \frac{r_a (R + r_{se})}{R \times r_{sh}} \right\}$$

The electrical efficiency of the ordinary compound dynamo is equal to the useful energy divided by the sum of the useful energy in the outside circuit, plus energy lost in series coils, plus energy lost in shunt coils, plus energy lost in armature.

$$\eta_e = \frac{E I}{E' I'} = \frac{I^2 R}{I^2 R + I^2 r_{se} + I_{sh}^2 r_{sh} + I'^2 r_a}$$

$$= \frac{I^2 R}{\frac{I^2 (r_{se} + r_{sh} + R)^2 r_a}{r_{sh}^2} + \frac{I^2 (r_{se} + R)^2}{r_{sh}} + I^2 R + I^2 r_{se}}$$

$$= \frac{1}{\frac{(r_{se} + r_{sh} + R)^2 r_a}{r_{sh}^2 R} + \frac{(r_{se} + R)^2}{r_{sh} R} + 1 + \frac{r_{se}}{R}}$$

For the **Long Shunt Compound-Wound Dynamo** (see Fig. 10) the equations may be written in a similar manner. The values of the total current generated will be

$$I' = I_{se} = I + I_{sh} = I + \frac{E}{r_{sh}} = I\frac{r_{sh} + R}{r_{sh}}$$

$$I_{sh} = \frac{E}{r_{sh}} = I\frac{R}{r_{sh}}$$

The total voltage generated in the armature is

$$E' = E + I'(r_a + r_{se}) = E + \left\{ I + \frac{E}{r_{sh}} \right\}(r_a + r_{se})$$

$$= E\left\{ 1 + \frac{R + r_{sh}}{R\, r_{sh}} \right\}(r_a + r_{se})$$

The electrical efficiency of the long shunt compound dynamo is

$$\eta_e = \frac{I^2 R}{I'^2(r_a + r_{se}) + I_{sh}^2 r_{sh} + I^2 R}$$

$$= \frac{I^2 R}{\left\{ I^2 + \frac{2RI^2}{r_{sh}} + \frac{R^2 I^2}{r_{sh}^2} \right\}(r_a + r_{se}) + \frac{I^2 R^2}{r_{sh}} + I^2 R}$$

$$= \frac{1}{\frac{r_a + r_{se}}{R} + 2\left\{ \frac{r_a + r_{se}}{r_{sh}} \right\} + \frac{R(r_a + r_{se})}{r_{sh}^2} + \frac{R}{r_{sh}} + 1}$$

NOTE.

DESIGN OF DYNAMOS.

The complete calculations for the design of a dynamo are very long and involved. Besides calling for considerable judgment on the part of the designer, they require the use of a number of constants whose values must be known from previous experience or must be determined by testing the machine itself after completion. The most difficult part of the calculation is the assignment of the proper values to these constants.

In the following pages are given the electrical and magnetic details for the design of a 50-kilowatt shunt dynamo. The method is taken from Mr. A. E. Wiener's "Dynamo Electric Machines," and the constants from tables in that work, to which the reader is referred for further details. Though in general a 50-kilowatt machine should be made multipolar, the bipolar type is here chosen. The method is better illustrated and the calculations are simpler. For the multipolar machine the principle is the same, but the details differ somewhat.

The dynamo is a machine for converting mechanical into electrical energy, and must therefore be designed from the mechanical point of view as well as the electrical. Armature, shaft, bearings and pulley are therefore subject to the ordinary rules for machine design; and experience indicates that very conservative design is necessary in the parts subject to mechanical stresses. The following section, however, is limited to the electrical and magnetic parts of the design.

Calculation of a Bipolar, Single Magnetic Circuit, Smooth-Drum, High-Speed Shunt Dynamo.

50 K.W. Upright Horseshoe Type. Wrought-Iron Cores and Yoke, Cast-Iron Polepieces.

250 Volts. 200 Amperes. 1050 Revs. per Min.

(*a*) Calculation of Armature.

1. Length of Armature Conductor.

An electromotive force of one volt is generated by a conductor that cuts 100,000,000 C. G. S. lines of force per second. As the English system of units is still the standard in this country, one foot will be taken as the unit length of conductor, one foot per second the unit linear velocity, and one magnetic line of force per square inch as the unit field strength. Then every foot (12 in.) of inductor, moving at the rate of one foot (12 in.) per second in a field having one magnetic line of force per square inch will generate an E. M. F. of

$$\frac{12 \times 12 \times 1}{100{,}000{,}000} = \frac{144}{10^8} \text{ volt.}$$

As the armature of an ordinary bipolar dynamo has two parallel conductors each generating the same E. M. F.; and as these conductors are in parallel, two feet of conductor will be used in generating 144×10^{-8} volt or in other words each foot of the total length of conductors will generate only 72×10^{-8} volt if moving at unit velocity in unit field.

As this theoretical value of "unit armature induction" assumes that there is a magnetic field entirely surrounding the armature, it will have to be modified so as to take into account the fact that the fringe of magnetic lines from the pole pieces only partially surround the armature. For a 50 K.W. bipolar dynamo with smooth-drum armature the polar arc (see Figure 1) may be taken for the present as about 124°. It is found from actual practice that for a machine having a polar arc of about 124°, the

unit armature induction will not be the theoretical value of 72×10^{-8} but will be about

$$e = 61 \times 10^{-8} \text{ volts.}$$

The "specific armature induction," *i. e.*, the induction per unit length of conductor moving at velocity v_c, in a magnetic field of strength, $\mathfrak{K}''$ will be

$$e' = e \times v_c \times \mathfrak{K}'' \text{ volts.}$$

where e' = specific induction of active armature conductor, in volts per foot of conductor;

e = unit armature induction per pair of armature circuits in volts per foot of conductor;

v_c = conductor-velocity, or cutting speed, in feet per second;

$\mathfrak{K}''$ = field density, in magnetic lines of force per square inch.

It is customary to take the conductor velocity v_c, as about 50 feet per second for a 50 K.W. bipolar dynamo having a drum armature; also to take the field density $\mathfrak{K}''$ as about 22,000 if the machine has cast iron pole pieces. Therefore the value of e' may be written,

$$e' = \frac{61 \times 50 \times 22{,}000}{100{,}000{,}000} = \frac{671}{1{,}000}$$

Knowing the specific armature induction, e', the voltage induced by one foot of conductor, and knowing the voltage, E', that the armature is required to induce, one may easily find the total length of *active* wire, L_a, of the armature.

$$L_a = \frac{E'}{e'} = \frac{E' \times 10^3}{671}$$

where L_a = total length of active conductor (on whole circumference opposite pole pieces);

E' = total E. M. F. to be generated in armature; *i. e.*, volt output plus additional volts to be allowed for drop due to internal resistance.

For a dynamo of 50 K.W. capacity it is necessary to add about 6% to the value of E, the voltage wanted by the external circuit, in order to get E', the total E. M. F. to be generated in the armature. If E is 250, E' is 106% of 250 or 265, and

$$L_a = \frac{265 \times 10^3}{671} = \textbf{395 feet of } \textit{active} \text{ conductor.}$$

The part of the conductor passing over the ends of the armature core is not active in cutting lines of magnetic force and so this

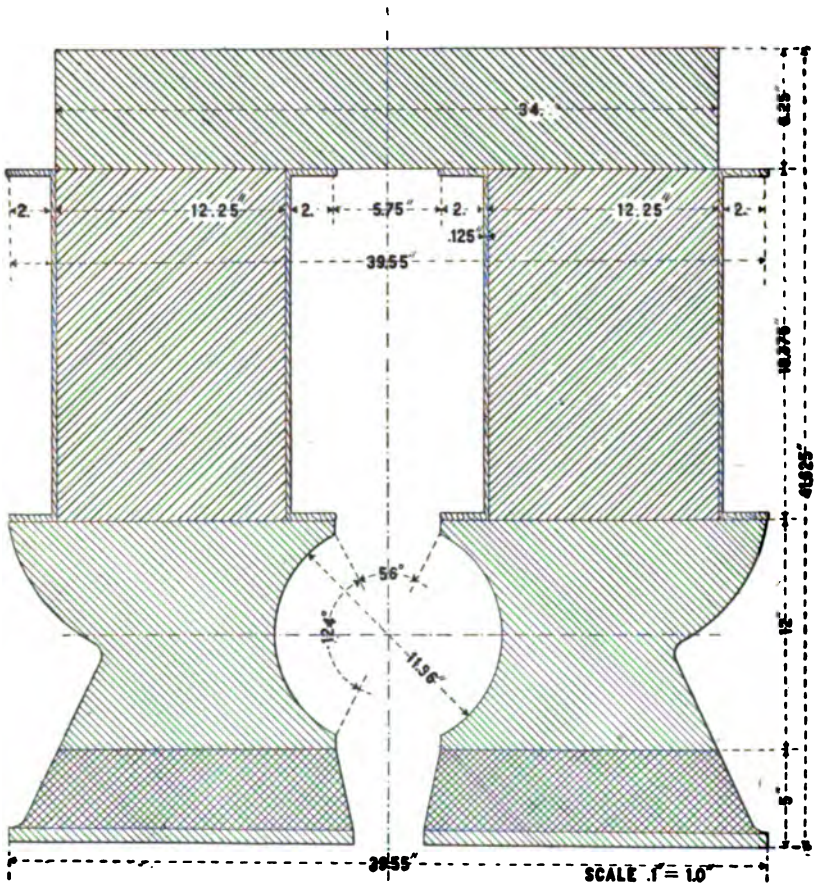


Fig. 1. Magnetic Circuit of 50 K.W. Dynamo.

length of conductor will have to be increased when the dimensions of the iron core of the armature are known.

2. Sectional Area of Armature Conductor, and Selection of Wire.

The cross section of wire to be chosen should be large enough so as not to be unduly heated by the current it has to carry. It is well to allow about 600 circular mils of copper conductor to 1

ampere of current, which is a current density of about 2,100 amperes per square inch of copper. Therefore to get the number of circular mils of copper to be provided multiply 600 by the current to be generated. There is to be furnished to the outside circuit 200 amperes. The armature will have to furnish this plus the current that goes through the shunt field. This latter value is so small however that it may be omitted with only trifling error or one may choose slightly larger wire for the armature than is needed for the 200 amperes. The cross section of conductor required therefore will be

200 × 600 circular mils or 120,000 circular mils.

As there are two conductors to carry this current each conductor should have 60,000 circular mils. By reference to the B. & S. wire table on page 28 it will be seen that No. 2 wire has a cross section of 66,371 circular mils.

As No. 2 wire is too stiff to wind on the armature, however,

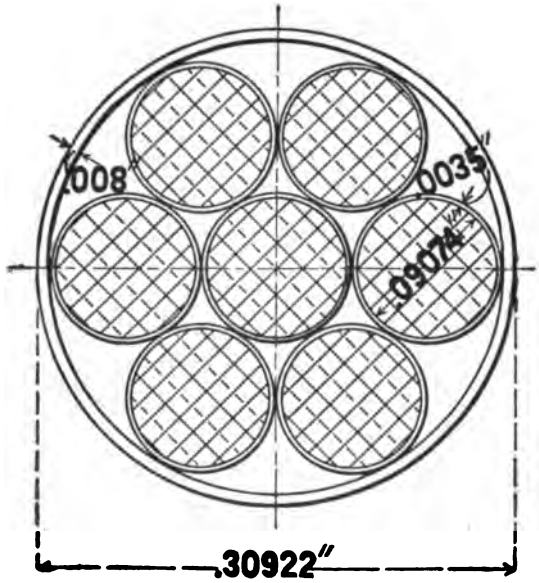


Fig. 2. Armature Conductor.

a cable made up of seven strands of No. 11 wire, having a copper cross section of 7 ×8,234 circular mils or a total of 57,638 circular mils is used. This will be a little higher current density than

was calculated upon at first but is not at all excessive. The diameter of No. 11 B. & S. wire is .09074 inch and a single cotton insulation of .007 inch is put on each strand and the seven strands are covered with a double cotton insulation of .016 inch. This will give the cable composed of seven strands of No. 11 B. & S. insulated wire a diameter (see Fig. 2) of

$$\delta'_s = 3 \times (.09074 \text{ inch} + .007 \text{ inch}) + .016 \text{ inch}$$
$$= \mathbf{.30922 \text{ inch.}}$$

3. Diameter of Armature Core.

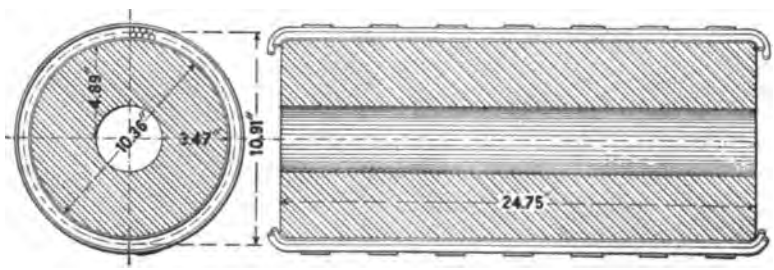
If the speed N is 1,050 revolutions per minute or $\frac{1050}{60}$ per second, and d'_a is the mean diameter of the armature winding in inches, or $\frac{d'_a}{12}$ in feet, then the cutting speed of the conductor in feet per second will be represented by,

$$v_c = \frac{d'_a \times \pi}{12} \times \frac{N}{60}$$

or

$$d'_a = \frac{12 \times 60}{\pi} \times \frac{v_c}{N} = \frac{12 \times 60 \times 50}{\pi \times 1050} = 10.91''.$$

It is found from actual practice that the ratio of the diameter of the armature, d_a, to the mean diameter of the armature



SCALE .1" = 1.0"

Fig. 3. Details of Armature.

winding, d'_a, is about .95 for drum armatures between eight and ten inches in diameter. Therefore (see Fig. 3)

$$d_a = .95 \text{ of } 10.91 \text{ inches, or } \mathbf{10.36 \text{ inches.}}$$

4. Length of Armature Core.

Knowing the number of conductors that can be laid on the surface of the armature core, and the available depth for the windings, one may easily determine the number of conductors that can be wound on the armature; and knowing this and the length of active armature conductor, the length of the armature core may be determined. For a machine generating less than 300 volts and having a drum armature of the size of the one under consideration about 8% of the surface of the armature core is given up to division strips or driving horns.

$$\text{Then } n_w = \frac{.92 \times d_a \times \pi}{\delta_a'}$$

$$= \frac{.92 \times 10.36 \times \pi}{.30922} = 97 \text{ or } 96.$$

where n_w = the number of armature wires per layer;
d_a = the diameter of the armature core, in inches;
δ'_a = the width of insulated armature conductor, in inches;
.92 = the portion of the surface to be occupied by the conductors.

For a drum armature of the size of the one under consideration the height of the windings should be about .55 of an inch and of this space about .06 inch will be taken up by the insulation between windings and the armature, and .05 inch by binding wires. This leaves a net height of about .44 of an inch for the conductor. Then the number of layers of conductors will be

$$n_1 = \frac{h'_a}{\delta''_a} = \frac{.44}{.30922} = 1\tfrac{1}{2} \text{ or } 2$$

where n_1 = number layers of armature wire;
h'_a = net height of winding space, in inches;
δ''_a = height of insulated conductor, in inches.

By dividing the length of active armature conductor by the number of conductors we obtain the length of one active conductor which is the length of the armature core (see Fig. 3).

$$l_a = \frac{12 \times L_a}{n_w \times n_1} = \frac{12 \times 395}{96 \times 2} = 24\tfrac{3}{4} \text{ inches approx.}$$

where l_a = length of armature core parallel to pole faces, in inches;
L_a = length of active armature conductor in feet;
n_w = number of wires per layer;
n_1 = number of layers of wire on armature.

5. Arrangement of Armature Windings.

For machines under 300 volts it is customary to have from 40 to 60 commutator segments. With this number of segments the voltage between two consecutive ones is low, and the pulsating current is within a fraction of one per cent of being a steady current. The number of commutator divisions, n_c, will be found by multiplying the number of wires per layer, n_w, by the number of layers, n_l, and dividing the product by some even number that gives a quotient which is between 40 and 60.

$$n_c = n_w \times n_l \div 4 = 48.$$

The number of convolutions per commutator segment, n_s will be

$$n_s = \frac{n_w \times n_l}{2 \times n_c} = \frac{96 \times 2}{2 \times 48} = 2$$

since it takes two conductors to make one turn. Therefore to sum up we have **48 coils**, each consisting of **2 turns** of a cable having **7 No. 11 B. & S. wires.**

6. Total Length of Armature Conductor, Weight and Resistance.

In order to connect the ends of the active conductors, turn the corners, etc., for this drum armature the total length of armature conductor will need to be about $1\frac{3}{4}$ times the active conductor.

$$L_t = 1.75 \times L_a = 1.75 \times 395 \text{ feet} = \textbf{691 feet.}$$

The weight of the conductor will be as follows: — A copper wire .001 in diameter weighs .00000303 pounds per foot of length. Therefore the weight of the total length of the copper in the armature conductor would be

$$wt_a = k_5 \times L_t \times \delta_a^2 \times .00000303$$
$$= 1.03 \times 691 \times 57638 \times .00000303 = \textbf{124 pounds}$$

where wt_a = weight of bare armature winding in pounds;

k_5 = ratio between weights of the insulated wire and bare wire;

L_t = total length of armature conductor in feet;

δ_a^2 = area of conductor in circular mils.

The **resistance** of the armature will be as follows: — The total length of armature wire 691 feet is arranged in two parallel

circuits 345½ feet long. These two paths are each composed of seven No. 11 B. & S. wires.

The resistance of 1,000 feet of No. 11 B. & S. wire is 1.311 ohms.

Therefore the resistance of the armature is,

$$R_a = \frac{1}{2 \times 7} \times \frac{345.5}{1{,}000} \times 1.311 \text{ ohms} = .0324 \text{ ohm.}$$

7. Radial Depth of Armature Core, Minimum and Maximum Cross Section, and Average Magnetic Density of Armature Core.

The following formula determines the proper size for the necessary strength of the armature shaft where it passes through the iron core of the armature.

$$d_c = k_2 \times \sqrt[4]{\frac{P'}{N}} = 1.3 \times \sqrt[4]{\frac{50{,}000}{1{,}050}} = 3.42 \text{ inches.}$$

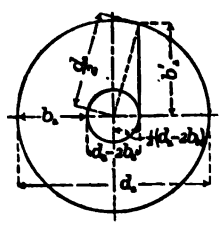


Fig. 4.

where d_c = diameter of armature shaft at core in inches;

P' = capacity of machine in watts;

N = speed, in revolutions per minute;

k_2 = constant depending upon capacity of machine.

Therefore the breadth of armature cross section, or radial depth of armature core is

$$b_a = \frac{1}{2}(d_a - d_c) = \frac{10.36 - 3.42}{2} = 3.47 \text{ inches.}$$

where b_a = radial depth of armature core, in inches;

d_a = diameter of armature core, in inches;

d_c = diameter of core section of armature shaft.

The maximum depth of armature core (see Fig. 4) is,

$$b'_a = \sqrt{\frac{d_a^2}{4} - \frac{(d_a - 2b_a)^2}{4}}$$

$$= \sqrt{\frac{(10.36)^2}{4} - \frac{(3.42)^2}{4}} = 4.89 \text{ inches.}$$

The cross section of the magnetic field in the armature is equal to

$$S''_{a1} = 2 \times l_a \times b_a \times k_2$$
$$= 2 \times 24.75 \times 3.47 \times .95 = \textbf{163 square inches.}$$
$$S''_{a2} = 2 \times l_a \times b'_a \times k_2$$
$$= 2 \times 24.75 \times 4.89 \times .95 = \textbf{230 square inches.}$$

where S''_{a1} = minimum cross section of armature core, in square inches;

S''_{a2} = maximum cross section of armature core, in square inches;

l_a = length of armature core, in inches;

b'_a = radial depth of armature core, in inches;

k_2 = ratio of net iron section to total cross section of armature core.

The useful magnetic flux in the armature may be obtained as follows: The

$$\text{E. M. F.} = \frac{\text{Number of C. G. S. lines cut per second}}{10^8}$$

$$E' = \frac{N \times N_c \times \Phi}{60 \times 10^8} \text{ volts}$$

where E' = total E. M. F. induced in armature;

N = number of armature revolutions per minute;

N_c = total number of conductors all around pole facing surface of armature;

Φ = total number of useful magnetic lines, in webers

or $$\Phi = \frac{60 \times 10^8 \times E'}{N \times N_c}$$

$$= \frac{60 \times 10^8 \times 265}{1050 \times 192} = \textbf{7,886,905 webers.}$$

Therefore the density of magnetic lines per square inch at the minimum cross section of the armature core is

$$\mathfrak{G}''_{a1} = \frac{7{,}886{,}905}{163} = \textbf{48,386 lines} \text{ per square inch.}$$

and the density at the maximum cross section is

$$\mathfrak{G}''_{a2} = \frac{7{,}886{,}905}{230} = \textbf{34,291 lines} \text{ per square inch.}$$

Next we wish to find the number of ampere-turns required to furnish this induction. The law for the magnetism in a magnetic circuit is exactly similar to the law for current in an electric circuit.

$$\text{Current (or Electric Flux)} = \frac{\text{Electromotive Force}}{\text{Resistance}}.$$

$$\text{Magnetic Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}.$$

Therefore the

$$\text{Magnetomotive Force} = \text{Magnetic Flux} \times \text{Reluctance}.$$

As the resistance of an electric circuit can be expressed by the specific resistance or resistivity of the material multiplied by the length of circuit and divided by the cross section, so the reluctance of a magnetic circuit can be expressed by the specific reluctance or reluctivity of the material multiplied by the length of the circuit and divided by the cross section. Therefore the

$$\text{Reluctance} = \text{Reluctivity} \times \frac{\text{Length}}{\text{Area}}.$$

As the conductivity of an electric circuit is the reciprocal of the resistivity, so the permeability of a magnetic circuit is the reciprocal of the reluctivity. Therefore the

$$\text{Reluctance} = \frac{\text{Length}}{\text{Permeability} \times \text{Area}}.$$

or

$$\text{Magnetomotive Force} = \frac{\text{Magnetic Flux} \times \text{Length}}{\text{Permeability} \times \text{Area}}.$$

and since the magnetic flux divided by the area is the magnetic density the formula is simplified by writing

$$\text{Magnetomotive Force} = \frac{\text{Magnetic Density} \times \text{Length}}{\text{Permeability}}.$$

The Unit of Field Density, or the magnetic density caused by a unit pole, is 1 line of magnetic force per square centimeter of field area and is termed 1 gauss.

A single Line of Force, or the Unit of Magnetic Flux, is that amount of magnetism that passes through every square centimeter of cross section of a magnetic field whose density is unity and is termed 1 weber.

The unit magnetic pole, or the pole of unit strength is that which repels an equal pole at unit distance with unit force. The lines of force are straight lines from the center of the sphere to the surface, there being one line to each square centimeter area on the surface. As the surface of a sphere having a radius of 1 centimeter has an area of 4π square centimeters, it follows that from a pole of unit strength there is a magnetic flux of 4π C. G. S. lines of magnetic force or 4π webers or 12.5664 webers.

One absolute C. G. S. unit of current, which is 10 times as large as the ampere, or ten amperes, flowing in a wire which is bent into a circle of one centimeter radius gives a C. G. S. unit magnetic pole at the center of curvature or 12.5664 webers. One practical unit or 1 ampere would cause one tenth as many webers or 1.25664 webers.

A long solenoid having a cross section of one square centimeter having 1 ampere ($\frac{1}{10}$ of the C. G. S. unit current) flowing per unit length of coil, has poles of $\frac{1}{10}$ unit strength which causes a magnetic flux of $\frac{1}{10} \times 4\pi$ webers.

The density of the magnetic circuit is $\frac{4\pi}{10}$ webers per square centimeter or $\frac{4\pi}{10}$ gausses.

The reluctance of unit length of the solenoid of one square centimeter cross section for air is unity or 1 oersted. The magnetomotive force is the product of the magnetic density, the reluctance and the length, and is measured in gilberts. Therefore the magnetomotive force required to produce a magnetic density of $\frac{4\pi}{10}$ gausses in a column of air one centimeter long and having a cross section of one square centimeter thus having a reluctance of 1 oersted is

$$\text{M. M. F.} = \frac{4\pi}{10} \times 1 \times 1 = \frac{4\pi}{10} \text{ gilberts.}$$

The magnetomotive force of $\frac{4\pi}{10}$ gilberts being produced by one ampere-turn, it follows that the

$$\text{Number of Ampere-turns} = \frac{10}{4\pi} \times \text{Number of Gilberts.}$$

The

Magnetizing Force = Specific Magnetizing Force × Length,

or the

Number of Ampere-turns = Ampere-turns per unit of Length × Length,

or $a\,t = f(\mathfrak{B}'') \times l$

where $a\,t$ = Ampere-turns required to magnetize a portion of a magnetic circuit;

$\mathfrak{B}''$ = density of the magnetic circuit per square inch;

$f(\mathfrak{B}'')$ = Specific magnetizing force, in ampere-turns per inch of length for the particular material and density employed; (this value of the magnetizing force must be taken from some table or induction curve as shown in Fig. 5, or found by experiment for the particular piece of iron to be used);

l = length of magnetic circuit of the material in inches.

To get the number of ampere-turns required to overcome the reluctance of the armature it is necessary to modify the above formula a little, as the value of $\mathfrak{B}''$ is not constant in all parts of the core.

$$f(\mathfrak{B}''_a) = \frac{1}{2}\left\{f(\mathfrak{B}''_{a1}) + f(\mathfrak{B}''_{a2})\right\}$$

$$= \frac{f(48{,}386) + f(34{,}291)}{2} = \frac{9.2 + 6.4}{2} = 7.8$$

It takes as seen from Fig. 5 about 9.2 ampere-turns to magnetize 1 inch of wrought iron to a density of 48,386 lines, and 6.4 ampere-turns to magnetize it to a density of 34,291 lines. Also 7.8 ampere-turns correspond to a density of **41,500 lines.**

8. Energy Losses in Armature, and Temperature Increase.

The energy lost in the armature due to the current in the armature conductors is

$$P_a = 1.2 \times (k_6 \times I)^2 \times r_a$$

$$= 1.2 \times (1.03 \times 200)^2 \times .0324 = \textbf{1650 watts}$$

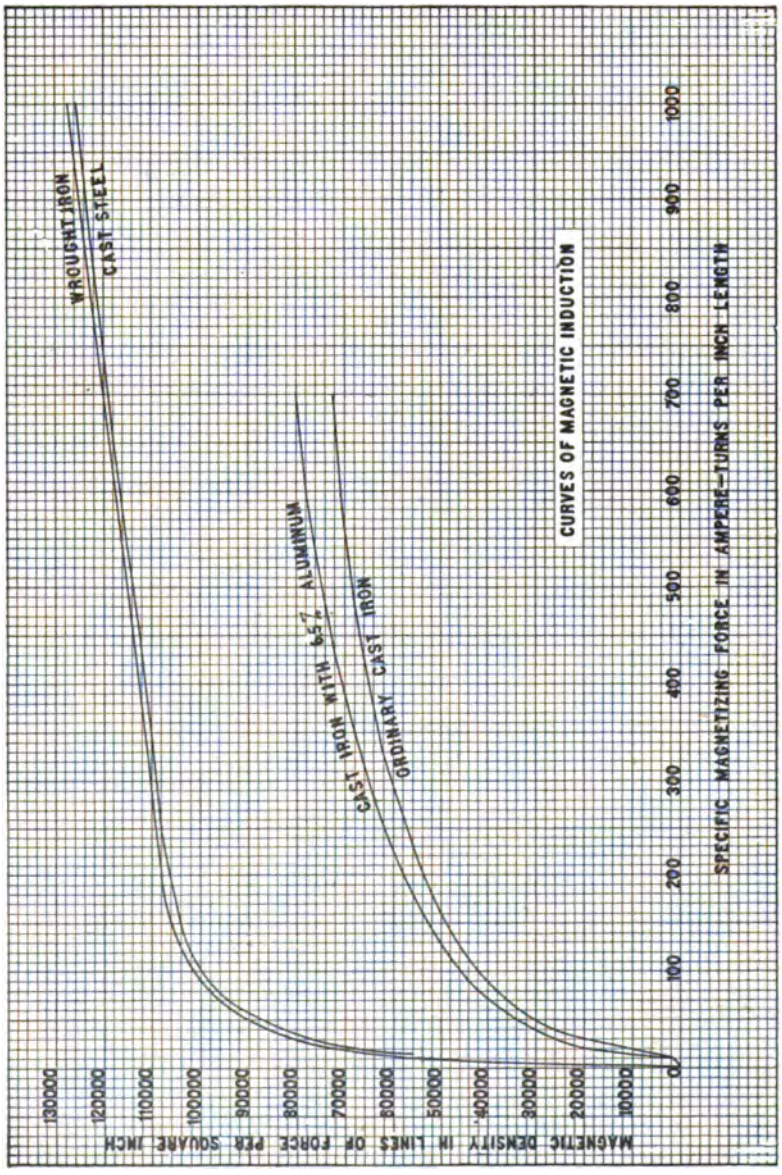

CURVES OF MAGNETIC INDUCTION
WROUGHT IRON
CAST STEEL
CAST IRON WITH 6% ALUMINUM
ORDINARY CAST IRON
MAGNETIC DENSITY IN LINES OF FORCE PER SQUARE INCH
130000
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
SPECIFIC MAGNETIZING FORCE IN AMPERE-TURNS PER INCH LENGTH
100
200
300
400
500
600
700
800
900
1000

Fig. 5.

where P_a = energy dissipated in armature winding, in watts;
r_a = resistance of armature winding cold, in ohms;
1.2 = ratio of resistance of armature winding hot, to resistance cold;
I = output of machine in amperes;
1.03 = ratio of total current generated to output.

The resistance of copper wire at 150° F. is about 1.2 times that at 60° F. The energy in the shunt coil of a 50 K.W. compound dynamo is about 3% of the output of the machine.

The loss in the armature core due to hysteresis is proportional to the 1.6th power of the magnetic density, directly proportional to the number of magnetic reversals, and directly proportional to the mass of the iron. Expressed in C. G. S. absolute units the energy consumed by hysteresis is,

$$P_h' = n_1 \times \mathfrak{B}_a^{1.6} \times N_1 \times M_1,$$
$$P_h' = n_1 \times \mathfrak{B}_a^{1.6} \times N_1 \times M_1',$$

where P'_h = energy lost due to hysteresis, in ergs;
n_1 = constant depending on magnetic hardness of material Hysteresis Resistance;
$\mathfrak{B}_a$ = density of lines per square centimeter of iron;
N_1 = frequency, or number of complete cyles of 2 reversals each, per second;
M_1' = mass of iron in cubic centimeters.

For soft sheet iron discs n_1 may be taken as .0035. In order to get the value of P_h' in practical units we must change the above equation. One watt equals 10^7 ergs. Instead of $\mathfrak{B}_a$ use the density $\mathfrak{B}_a''$ in lines per square inch.

$$N_1 = \frac{N}{60} = \frac{1050}{60} = 17\tfrac{1}{2}.$$

One cubic foot equals 28,316 cubic centimeters. The mass of iron in the armature in cubic feet is

$$M = \frac{d_a''' \times \pi \times b_a \times l_a \times k_2}{1{,}728}$$

$$= \frac{(10.36 - 3.47) \times \pi \times 3.47 \times 24.75 \times .95}{1728} = 1.02 \text{ cubic ft.},$$

where M = net mass of iron, in cubic feet;

d_a''' = mean diameter of armature core, in inches,

$= d_a - b_a$, (see Fig. 4);

l_a = length of armature core, in inches;

b_a = radial depth of armature core, in inches;

k_2 = ratio of net iron section to total iron section.

There are 1,728 cubic inches in 1 cubic foot. Expressing the value of the energy lost by hysteresis in practical units we have,

$$P_h = 10^{-7} \times .0035 \times \left\{ \frac{\mathfrak{G}_a''}{6.45} \right\}^{1.6} \times 28{,}316 \times N_1 \times M,$$

where P_h = energy lost by hysteresis, in watts;

$\mathfrak{G}_a''$ = density, in lines per square inch, corresponding to average magnetizing force required for armature core, (1 square inch = 6.45 square centimeters);

N_1 = frequency, in cycles per second;

M = net mass of iron in armature, in cubic feet.

By reducing the above expression to simple form, we have

$$P_h = 5 \times 10^{-7} \times \mathfrak{G}_a''^{1.6} \times N_1 \times M,$$

$$= 5 \times 10^{-7} \times (41{,}500)^{1.6} \times 17\tfrac{1}{2} \times 1.02 = 219 \text{ watts.}$$

Eddy Currents.

It has been explained under *Electromagnetic Induction* (see "Theory of Dynamo Electric Machinery") by what means and methods electromotive forces, and consequently electrical currents are set up in closed conductors. It is clear that any mass of metal moving in a field is a closed conductor. A loop of wire may have currents generated in it quite as easily if it be made part of a metallic disc as if it were still a loop. Since the lines of force can only cut a solid piece of metal once, the electromotive force that will be generated, unlike that in a coil of many turns cut by the same field, will be very small. But if the piece of metal be large the resistance will be very small so that the current which is induced may reach considerable strength and cause much heating. This action is largely prevented from taking place in the armature cores of dynamos by building them up of thin sheets of iron. The sheets are insulated from each other and are placed in such a

direction as to cut across the path which would be followed by the induced current. This method of construction is termed lamination, and it is necessary to build all iron or metallic parts which are not intended to act as conductors in this way, if they are likely to be subjected to fields of varying strength. This is the case in alternating current machinery and in the moving parts of direct current machinery. Sometimes even conductors, if they are very large, have local currents generated in them which are of course undesirable because they are a source of waste and heat, and it becomes necessary to laminate them. In this case the lamination would be parallel to the length of the conductor. Heavy conductors are usually laminated or stranded any way for greater ease in construction. Eddy currents are often called Foucault currents from Foucault who first called attention to their existence.

The energy lost by eddy currents is found to be proportional to the square of the magnetic density, to the square of the frequency, and to the mass. The equation for the lost energy due to eddy currents is,

$$P_e' = \epsilon' \times \mathfrak{B}_a^2 \times N_1^2 \times M'_1;$$

where P_e' = lost energy due to eddy currents, in ergs;
$\mathfrak{B}_a$ = density of lines of force, per square centimeter of iron;
N_1 = frequency, in cycles per second;
M_1' = mass of iron, in cubic centimeters;
ϵ' = eddy current constant, depending upon the thickness and the specific electric conductivity of the material;

$$\epsilon' = \frac{\pi^2}{6} \times \delta^2 \times \gamma \times 10^{-9}$$

$$= 1.645 \times \delta^2 \times \gamma \times 10^{-9}$$

where δ = thickness of sheet iron, in centimeters;
γ = electrical conductivity, in mhos;
γ = 100,000 for iron.

By changing to practical units and simplifying the above equation,

$$P_e = 10^{-7} \times 1.645 \times (2.54\ \delta_1)^2 \times 10^{-4} \times \left\{ \frac{\mathfrak{B}_a''}{6.45} \right\}^2 \times N_1^2$$

$$\times\ 28{,}316 \times M = 7.22 \times 10^{-8} \times \delta_1^2 \times \mathfrak{B}_a''^2 \times N_1^2 \times M.$$

where δ_1 = thickness of iron laminæ in armature, in fractions of an inch;

$\mathfrak{B}_a''$ = density, in lines per square inch, corresponding to average specific magnetizing force of armature core;

N_1 = frequency in cycles per second;

M = mass of iron, in cubic feet.

The terms 7.22, 10^{-8}, δ_1^2, and $\mathfrak{B}_a''^2$, may be multiplied together to form the eddy current factor ϵ, and then the formula for loss due to eddy currents becomes,

$$P_e = \epsilon \times N_1^2 \times M$$

$$= .0125 \times (17\tfrac{1}{2})^2 \times 1.02 = 4.\ \text{watts}.$$

For $\epsilon = .0125$ when the thickness of the sheet iron discs is .01″ and when the magnetic density is 41,500 lines.

The total energy loss in the armature is

$$P_A = P_a + P_h + P_e = 1650 + 219 + 4$$

$$= 1873\ \text{watts} = 2.5\ \text{h. p.}$$

Knowing the amount of electrical energy lost in the armature and dissipated as heat, and knowing the dimensions and speed of the armature it is possible, by using certain known constants that have been found by experience, to calculate quite exactly the rise of temperature in the armature and to calculate the hot resistance of the copper in the armature conductors. These details are somewhat complicated and will not be treated.

(*b*) Dimensions of Magnet Frame.

1. Total Magnetic Flux, and Sectional Area of Magnet Frame.

The total magnetic flux to be generated in a dynamo is the useful magnetic flux multiplied by a factor of magnetic leakage. Knowing the shape of the various parts of the magnetic circuit and the reluctance of the parts of the magnetic circuit and the sur-

rounding air circuits, it is possible to determine the amount of magnetic leakage, or waste magnetism.

$$\Phi' = \lambda \times \Phi = 1.35 \times 7{,}886{,}905 = 10{,}647{,}322 \text{ webers}$$

where Φ' = total flux to be generated in dynamo, in lines of force;

Φ = useful flux necessary to produce the required E. M. F.;

λ = factor of magnetic leakage, which for a 50 K.W. bipolar machine of the Edison type is found to be about 1.35.

The sectional area of the magnet frame is expressed by the formula,

$$S''_m = \frac{\Phi'}{\mathfrak{B}''_m} = \frac{10{,}647{,}322}{90{,}000} = \textbf{118 square inches}$$

where S''_m = cross section of wrought iron magnet core and of yoke, in square inches;

Φ' = total flux, in webers;

$\mathfrak{B}''_m$ = magnetic density of magnet frame, which for wrought iron magnet cores and yoke is taken as 90,000 lines per square inch.

The Practical Limit of Magnetization for cast iron pole pieces is taken as 50,000 lines per square inch.

$$S''_m = \frac{\Phi'}{\mathfrak{B}''_m} = \frac{10{,}647{,}322}{50{,}000} = \textbf{213 square inches.}$$

2. Sectional Area of Magnet Frame.

If the magnet core is in the form of a cylinder the diameter will be

$$d_m = \sqrt{\frac{4}{\pi} \times 118} = 12.25 \text{ inches.}$$

For a circular magnet core carrying about 10,000,000 lines of force the most economical ratio of length to diameter of magnet core is found to be about 1.5. Hence

$$l_m = 1.5 \times d_m = 18.375 \text{ inches.}$$

For a machine having an armature between 10 and 11 inches in diameter the distance, c, between magnet cores is taken as about

$$c = 5\tfrac{3}{4} \text{ inches.}$$

Take the width of the wrought iron yoke a little greater than

the diameter of the magnet cores so as to form a mechanical protection to them. Let this width be $18\frac{3}{4}$ inches. Then the height of the yoke would be

$$h_y = \frac{118}{18\frac{3}{4}} = 6\tfrac{1}{4} \text{ inches.}$$

The pole pieces are determined as follows: — The bore of the pole pieces is the sum of the diameter of the armature core, the winding, the insulation and binding, and the air gaps, which for a drum armature of this diameter is taken as about .14″.

$$\text{Diam. of bore} = 10.36'' + 4 \times .30922'' + 2 \times .11'' + .14'' = 11.96''.$$

In order to keep the corners of the pole pieces far enough apart so that there will not be too much leakage across, the distance is taken from 1.25 to 8 times the length of the two air gaps according to the size and type of dynamo.

$$l'_p = k_{11} \times (d_p - d_a) = 4. \times (11.86 - 10.36) = 6.00 \text{ inches.}$$

where l'_p = distance between pole corners, in inches;
d_p = diameter of bore of pole pieces, in inches;
d_a = diameter of iron core of armature, in inches;
k_{11} = 4. for drum armature of a 50 K.W. bipolar dynamo.

Let the length of the pole pieces equal the length of iron core in armature, or

$$l_p = 24\tfrac{3}{4}''.$$

Let the height of pole pieces equal the diameter of bore approx.

$$h_p = 12''.$$

The thickness at the center which carries only half the lines will be

$$\frac{213}{2 \times 24\frac{3}{4}} = 4.3 + \text{ or } 4\tfrac{3}{8}''.$$

In order to provide a non-magnetic base through which the magnetic lines will not leak from pole to pole a block of zinc about 5 inches thick should be placed under the dynamo.

(c) Calculation of Magnetizing Forces.

1. Air Gaps.

The length of the two air gaps is

$$l''_g = k_{12} \times (d_p - d_a) = 1.4 \times 1.5'' = 2.1''$$

where l''_g = length of path of magnetic lines across the two air gaps;

d_p = diameter of bore of pole pieces, in inches;

d_a = diameter of iron core of armature, in inches;

k_{12} = constant depending on the path of the lines of force through the air gap. The lines of force pass through the gaps obliquely owing to the distortion of the magnetic field and the constant, k_{12}, grows greater as the velocity of the conductor, v_c, and the density, $\mathfrak{K}$, are greater. If the product of v_c and $\mathfrak{K}$ is above 2,000,000 the value of k_{12} is taken as 1.4.

The cross section of the magnetic field of the air gap is represented by,

$$S_f = d_f \times \frac{\pi}{2} \times \beta'_1 \times l_f$$

$$= 11.11'' \times \frac{\pi}{2} \times .84 \times 24\tfrac{3}{4} = 363 \text{ square inches}$$

where S_f = the area occupied by the effective conductors, in square inches;

d_f = mean diameter of magnetic field in inches;

$= \frac{1}{2}(d_a + d_p)$;

l_f = breadth of magnetic field, in inches;

β'_1 = ratio of effective field circumference, depending upon the percentage of polar embrace, here taken as .84.

The actual field density in air gaps is found by dividing the value of the total useful flux in webers, by the area of the magnetic field of air gap.

$$\mathfrak{K}'' = \frac{\Phi}{S_f} = \frac{7{,}886{,}905}{363} = 21{,}727 \text{ lines per square inch.}$$

The number of ampere-turns required to produce this magnetic density in the air gaps is,

$$a\,t_g = \frac{10}{4\pi} \times \mathfrak{K}'' \times \frac{l''_g}{2.54} = .3133 \times \mathfrak{K}'' \times l''_g$$

$$= .3133 \times 21{,}727 \times 2.1 = \textbf{14,295 ampere-turns.}$$

2. Armature Core.

The average length of the magnetic paths in the armature is (see Fig. 6).

$$l''_a = d'''_a \times \pi \times \frac{90° + a}{360°} + b_a$$

$$= 6.89'' \times \pi \times \frac{90 + 28}{360} + 3.47'' = \textbf{10.57 inches.}$$

where l''_a = length of magnetic path in armature core, in inches;
d'''_a = mean diameter of armature core, in inches;
b_a = radial depth of armature core, in inches;
a = half angle between adjacent pole corners.

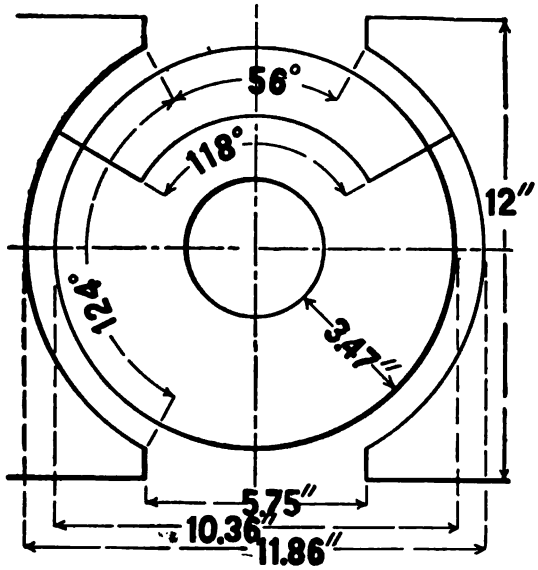


Fig. 6. Magnetic Details of Armature Core.

As previously determined the minimum cross section of the armature core is,

S''_{a1} = 163 square inches,

and the maximum cross section is

S''_{2a} = 230 square inches.

The average specific magnetizing force to magnetize the armature core to the required density will be

$$f(\mathfrak{B}''_a) = \frac{f(48{,}386) + f(34{,}291)}{2} = 7.8 \text{ ampere-turns.}$$

The total magnetizing force required to magnetize the armature is

$a\,t_a = 10.57 \times 7.8 =$ **82 ampere-turns.**

3. Wrought Iron Field Cores and Yoke.

The length of the magnetic path through the wrought iron cores and the yoke will be (see Fig. 1),

$l''_{w.i.} = 2 \times 18\frac{3}{4} + 6\frac{1}{4} + 18 =$ **61 inches.** (approx.)

The density of the field has already been decided upon as 90,000 lines per square inch. It has been determined by experiment that a specific density of 90,000 lines in wrought iron is produced by 50.7 ampere turns.

The total length of magnetic circuit through field cores and yoke will require

$a\,t_{w.i.} = 61 \times 50.7 =$ **3093 ampere-turns.**

4. Cast Iron Pole Pieces.

The average length of the magnetic path through the pole pieces may be taken as the average of the longest path and the shortest path. In the present case it is about

$l''_{c.i.} = 15$ inches.

The minimum cross section at the center of the pole piece which carries only half the lines has already been taken as

$S_{c.i.1} = 106.5$ square inches

which corresponds to a density of

$\mathfrak{B}''_{c.i.} = 50{,}000$ lines per square inch.

The maximum cross section of the magnetic circuit in pole pieces is the area of the pole face and is

$$S_{c.i.2} = 11.86 \times \pi \times \frac{124}{360} \times 24.75 = 318 \text{ square inches,}$$

which corresponds to a minimum density of

$$\mathfrak{B}''_{c.i.2} = \frac{7{,}886{,}905}{318} = 24802 \text{ magnetic lines.}$$

The average specific magnetizing force will be

$$f(\mathfrak{B}''_{c.i.}) = \tfrac{1}{2}\,[f(50{,}000) + f(24{,}802)] = \frac{160 + 88.6}{2}$$

$$= 99.3 \text{ ampere-turns,}$$

which corresponds to average density of 42,175 lines.

Then the total number of ampere-turns required to magnetize pole pieces is

$$a\,t_{c.l.} = 15 \times 99.3 = \textbf{1490 ampere turns.}$$

5. Armature Reactions.

The demagnetizing and cross-magnetizing effects caused by the ampere-turns of the armature oppose the magnetizing effect of the field coils and have to be overcome by adding more ampere-turns to those required to overcome the reluctance of the circuit.

The number of ampere-turns required to balance the armature reaction is,

$$a\,t_r = k_{14} \times \frac{N_a \times I'}{2} \times \frac{k_{13} \times a}{180°}$$

$$= 1.71 \times \frac{96 \times 200}{2} \times \frac{28}{180} = \textbf{2554 ampere-turns}$$

where $a\,t_r$ = ampere-turns required to compensate for armature reactions;

k_{14} = being a constant depending upon the magnetic density in pole pieces;

N_a = total number of turns on armature;

I' = total armature current in amperes;

2 = number of armature circuits for current;

$k_{13} \times a$ = angle of brush lead, which is nearly equal to half the angle between two pole corners, for smooth drum armatures.

The total number of ampere-turns required on field coils of dynamo will be the sum of all the ampere-turns required for the various parts of the circuit.

$$AT' = at_g + at_a + at_{w.l.} + at_{c.l.} + at_r$$

$$= 14{,}295 + 82 + 3093 + 1490 + 2554$$

$$= \textbf{21,514 ampere-turns.}$$

(*d*) Calculation of Magnet Winding.

The shunt winding should be calculated for a temperature increase of about 15°C above the normal temperature. (If desired

the shunt coil may be calculated so as to give a higher voltage to the dynamo which can be decreased by a regulating resistance in series with the shunt coil. As this calculation is not required in order to show the electromagnetic theory of the dynamo it will not be discussed here. It requires a recalculation of the magnetic flux for the various parts of the magnetic circuit and a recalculation of the corresponding ampere-turns.)

1. Magnet Winding.

The mean length of one turn of wire on the field core is

$$l_{\mathrm{T}} = k_{17} \times d_{\mathrm{m}} = 3.66 \times 12\tfrac{1}{4}'' = 44.8''$$

where k_{17} = a constant, depending upon the size of the field core, giving the ratio of the length of a mean turn to the core diameter.

The specific length of magnet shunt wire in feet per ohm is given by the formula,

$$\lambda_{\mathrm{sh}} = \frac{L_{\mathrm{sh}}}{r_{\mathrm{sh}}}$$

$$= \frac{AT}{E} \times \frac{l_{\mathrm{T}}}{12} \times (1 + .004 \times \theta_{\mathrm{m}})$$

$$= \frac{21{,}514}{250} \times \frac{44.8}{12} \times (1 + .004 \times 15)$$

$$= 340.5 \text{ feet per ohm.}$$

No. 15 B & S has 315 feet per ohm.

No. 14 B & S has 397 feet per ohm.

Use about No. 14 B & S wire.

The height of the winding space is given by the formula

$$h_{\mathrm{m}} = \frac{l_{\mathrm{T}}}{\pi} - d_{\mathrm{m}} = \frac{44.8}{\pi} - 12.25 = 2 \text{ inches.}$$

The radiating surface of the magnet coils will be

$$S_{\mathrm{M}} = (12.25 + 2 \times 2)\ \pi \times 2\ (18.375) = 1877 \text{ square inches.}$$

The energy absorbed in the magnet winding may be expressed by the formula,

$$P_{sh} = \frac{\theta_m}{75} \times S_M$$

$$= \frac{15}{75} \times 1877 = \textbf{375 watts.}$$

where P_{sh} = watts absorbed in field winding;

θ_m = rise of temperature in magnets, in degrees Centigrade;

S_M = radiating surface of magnet coils.

$$I_{sh} = \frac{P_{sh}}{E} \quad \text{or } I_{sh}\, E = P_{sh}.$$

Therefore the number of shunt turns may be found by

$$N_{sh} = \frac{A\,T}{I_{sh}} = \frac{A\,T \times E}{P_{sh}}$$

$$= \frac{21514 \times 250}{375} = \textbf{14,343 shunt turns.}$$

The length of the shunt winding is

$$L_{sh} = \frac{14{,}343 \times 44.8}{12} = \textbf{53,547 feet.}$$

The resistance of the shunt wire will be

$$r_{sh} = \frac{53{,}547}{340.5} = \textbf{157 ohms,} \text{ at } 15.5^\circ \text{ C.}$$

The warm resistance at 30.5° C is

$$r_{sh} = 157 \times (1 + .004 \times 15) = \textbf{166 ohms.}$$

The shunt current at full load is

$$I_{sh} = \frac{250}{166} = \textbf{1.5 amperes.}$$

If desired it is a simple matter to get the weight of the wire used.

(*e*) Calculation of Efficiency.

The electrical efficiency of the dynamo is the ratio of the available energy to the available energy plus the energy lost due to armature resistance plus that due to field coil resistance.

$$\eta_e = \frac{P}{P + P_a + P_M}$$

$$= \frac{250 \times 200}{250 \times 200 + 1.06 \times 201.5^2 \times .0324 + 1.5^2 \times 166}$$

$$= .96 \text{ or } \mathbf{96\% \text{ electrical efficiency.}}$$

The commercial efficiency is the ratio of the output, to the sum of the output, wire loss in armature, wire loss in field, hysteresis loss, eddy current loss, and friction loss (which we will assume as 2,500 watts).

$$\eta_c = \frac{P}{P + P_a + P_M + P_h + P_e + P_o}$$

$$= \frac{50{,}000}{50{,}000 + 1{,}394 + 374 + 219 + 4 + 2{,}500}$$

$$= .917 \text{ or } \mathbf{91.7\%, \text{ commercial efficiency.}}$$

WIRE TABLE. PROPERTIES OF COPPER WIRE.

Number B. & S. Gauge.	Diameter "d" in Mils. 1 Mil = .001 Inch.	Area in Circular Mils d^2.	Area in Thousandths of an Inch $d^2 \times .7854$.	Weight per Unit of Length. Specific Gravity, 8.89. Pounds per 1000 Feet.	Pounds per Mile.	Feet per Pound.	Ohms per Pound, Annealed.	Resistance in International Ohms at 68° F. According to Matthiessen's Standard of Resistivity. Ohms per 1000 Ft. Annealed.	Ohms per 1000 Ft. Hard-Drawn.	Ohms per Mile. Annealed.	Ohms per Mile. Hard-Drawn.	Feet per Ohm Annealed.	Tensile Strength in Pounds. Annealed.	Tensile Strength in Pounds. Hard-Drawn.	Elong. % in 1 Foot. Annealed.	Elong. % in 1 Foot. Hard-Drawn.	Safe Current in Amperes. Bright Wire Paneled.	Safe Current in Amperes. Black Wire in Free Air.	Turns per Lin. In. Cotton Covered.	Temperature Coefficients. Temp. in Deg. C.	Temperature Coefficients. Resistance per Mil-Foot; Ohms.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0000	460.000	211600.00	.166190	640.5	3381.4	1.561	.00007638	.04893	.050036	.25835	.26419	20440	5650	9975	45.0	5.00	146.0	346.0	1.6	0	1.00000
000	409.642	167806.43	.131794	508.0	2682.2	1.969	.0001215	.06170	.063094	.32577	.33314	16210	4475	7900	45.0	5.00	127.0	292.0	1.6	1	1.00397
00	364.796	133076.65	.104518	402.8	2126.8	2.482	.0001931	.07780	.079558	.41079	.42007	12850	3550	6250	45.0	4.00	110.0	247.0	1.8	2	1.00776
0	324.861	105534.50	.082857	319.5	1686.9	3.130	.0003071	.09811	.10033	.51802	.52973	10900	2800	4950	45.0	4.00	95.0	209.0	2.8	3	1.01166
1	289.296	83692.67	.065732	253.3	1337.2	3.947	.0004883	.1237	.12649	.65314	.66790	8063	2225	3925	42.0	4.00	83.0	177.0	3.2	4	1.01558
2	257.626	66371.31	.052128	200.9	1060.6	4.977	.0007765	.1560	.15953	.82368	.84239	6410	1750	3125	39.0	3.00	72.0	148.0	3.4	5	1.01950
3	229.422	52634.37	.041339	159.3	841.09	6.276	.001235	.1967	.20114	1.0386	1.0621	5084	1400	2450	36.0	3.00	63.0	127.0	3.9	6	1.02343
4	204.307	41741.32	.032784	126.4	667.39	7.914	.001936	.2480	.25361	1.3094	1.3392	4031	1100	1950	33.0	2.50	55.0	106.0	4.5	7	1.02738
5	181.941	33102.37	.025999	100.2	529.06	9.980	.003122	.3128	.31987	1.6516	1.6889	3197	875	1550	30.5	2.50	48.0	91.0	5.0	8	1.03134
6	162.022	26251.37	.020618	79.46	419.55	12.58	.004963	.3944	.40332	2.0825	2.1295	2535	700	1225	28.0	2.00	42.0	78.0	5.6	9	1.03531
7	144.285	20818.35	.016351	63.02	332.75	15.87	.007892	.4973	.50854	2.6258	2.6850	2011	550	975	26.0	2.00	37.0	66.0	6.2	10	1.03929
8	128.490	16509.64	.012967	49.98	263.89	20.01	.01255	.6271	.64127	3.3111	3.3859	1595	425	775	24.0	1.75	32.0	56.0	7.0	11	1.04328
9	114.434	13092.75	.010283	39.63	209.24	25.23	.01995	.7908	.80876	4.1753	4.2769	1265	325	600	21.5	1.75	28.2	48.0	7.5	12	1.04728
10	101.897	10383.02	.0081548	31.43	165.95	31.82	.03173	.9972	1.0199	5.2657	5.3848	1003	275	475	19.0	1.50	24.9	41.0	8.5	13	1.05129
11	90.743	8234.11	.0064656	24.93	131.63	40.12	.05045	1.257	1.2854	6.6369	6.7869	795.3	200	375	17.5	1.50	21.9	35.0	9.7	14	1.05532
12	80.808	6529.95	.0051287	19.77	104.39	50.58	.08022	1.586	1.6218	8.3741	8.5633	630.7	175	300	16.0	1.25	19.3	30.0	11.2	15	1.05935
13	71.962	5178.48	.0040672	15.68	82.791	63.79	.1276	1.999	2.0443	10.555	10.794	500.1	125	225	14.5	1.25	17.0	25.8	12.0	16	1.06339
14	64.084	4106.72	.0032254	14.43	76.191	80.44	.2028	2.521	2.5779	13.311	13.612	396.6	100	200	13.0	1.25	15.0	22.2	13.0	17	1.06745
15	57.089	3256.78	.0025579	9.858	52.050	101.4	.3225	3.179	3.2508	16.785	17.165	314.5	80	150	12.0	1.25	13.3	19.1	15.3	18	1.07153
16	50.821	2582.74	.0020285	7.818	41.277	127.9	.5128	4.009	4.0996	21.168	21.646	249.4	60	125	11.0	1.25	11.8	16.5	16.7	19	1.07559
17	45.257	2048.29	.0016087	6.200	32.736	161.3	.8153	5.055	5.1692	26.691	27.294	197.8	50	90	10.0	1.25	10.4	14.2	17.7	20	1.07968
18	40.303	1624.30	.0012757	4.917	25.960	203.4	1.296	6.374	6.5180	33.655	34.416	156.9	40	70	9.0	1.25	9.2	12.3	19.5	21	1.08378
19	35.890	1288.13	.0010117	3.899	20.585	256.5	2.061	8.038	8.2196	42.441	43 400	124.4	30	60	8.0	1.20	8.2	10.7	22.7	22	1.08788
20	31.961	1022.53	.00080231	3.092	16.324	323.4	3.278	10.14	10.372	53.539	54.749	98.66	25	45	7.0	1.20	7.2	9.2	27.0	23	1.09200
21	28.463	810.12	.00063626	2.452	12.946	407.8	5.212	12.78	. . .	67.479	. . .	78.94	23	39	6.0	1.00	. . .	. . .	31.0	24	1.09612
22	25.346	642.45	.00050457	1.945	10.268	514.2	8.287	16.32	. . .	85.114	. . .	62.05	21	32	5.0	1.00	. . .	. . .	34.4	25	1.10026
23	22.572	509.49	.00040015	1.542	8.142	648.4	13.18	20.32	. . .	107.29	. . .	49.21	18	28	5.0	1.00	. . .	. . .	38.2	26	1.10440
24	20.101	404.04	.00031733	1.223	6.457	817.6	20.95	25.63	. . .	135.33	. . .	39.02	16	20	5.0	1.00	. . .	. . .	42.3	27	1.10856
25	17.901	320.42	.00025166	.9699	5.121	1031	33.32	32.31	. . .	170.59	. . .	30.95	12	16	5.0	1.00	. . .	. . .	47.0	28	1.11272
26	15.940	254.10	.00019958	.7692	4.061	1300	52.97	40.75	. . .	215.16	. . .	24.54	. .	. .	. .	. .	. . .	. . .	52.0	29	1.11689
27	14.196	201.52	.00015827	.6100	3.221	1639	84.23	51.35	. . .	271.29	. . .	19.46	. .	. .	. .	. .	. . .	. . .	57.0	30	1.12107
28	12.642	159.81	.00012551	.4837	2.554	2067	133.9	64.70	. . .	342.09	. . .	15.43	. .	. .	. .	. .	. . .	. . .	63.4	40	1.16332
29	11.258	126.74	.00009836	.3836	2.025	2607	213.0	81.70	. . .	431.37	. . .	12.24	. .	. .	. .	. .	. . .	. . .	70.1	50	1.20625
30	10.025	100.51	.00007936	.3042	1.606	3287	338.6	103.0	. . .	543.84	. . .	9.707	. .	. .	. .	. .	. . .	. . .	77.1	60	1.24965
31	8.928	79.70	.00006259	.2413	1.274	4145	538.4	129.9	. . .	685.87	. . .	7.698	. .	. .	. .	. .	. . .	. . .	84.6	70	1.29327
32	7.950	63.20	.00004963	.1913	1.010	5227	856.2	163.8	. . .	864.87	. . .	6.105	. .	. .	. .	. .	. . .	. . .	92.7	80	1.33681
33	7.080	50.13	.00003868	.1517	.801	6591	1361	206.6	. . .	1090.8	. . .	4.841	. .	. .	. .	. .	. . .	. . .	101.6	90	1.37995
34	6.305	39.78	.00003121	.1203	.635	8311	2165	260.5	. . .	1375.5	. . .	3.839	. .	. .	. .	. .	. . .	. . .	112.1	100	1.42231
35	5.615	31.52	.00002479	.09543	.504	10482	3441	328.4	. . .	1734.0	. . .	3.045	. .	. .	. .	. .	. . .	. . .	119.7	. .	. . .
36	5.000	25.00	.00001963	.07566	.400	13217	5473	414.2	. . .	2187.0	. . .	2.414	. .	. .	. .	. .	. . .	. . .	130.6	. .	. . .
37	4.453	19.83	.00001557	.06001	.317	16666	8702	522.2	. . .	2757.3	. . .	1.915	. .	. .	. .	. .	. . .	. . .	140.6	. .	. . .
38	3.965	15.72	.00001234	.04759	.251	21015	13870	658.5	. . .	3476.8	. . .	1.519	. .	. .	. .	. .	. . .	. . .	151.0	. .	. . .
39	3.531	12.46	.00000978	.03774	.199	26500	22000	830.4	. . .	4384.5	. . .	1.204	. .	. .	. .	. .	. . .	. . .	163.4	. .	. . .
40	3.145	9.88	.00000776	.02993	.158	33416	34980	1047.0	. . .	5528.2	. . .	.955	. .	. .	. .	. .	. . .	. . .	177.6	. .	. . .

WIRE TABLE. INSULATED WIRE.

Gauge of Wire.		Diameter of Wire (bare).		Single Cotton Insulation.				Double Cotton Insulation.			
B. W. G.	B. & S.	inch	mm	Thickness of insulation. Inch.	Ratio of bare diameter to thickness of insulation.	Weight of insulation per 100 lbs. of covered wire.	Weight of covered wire per lb. of bare wire, k_2.	Thickness of insulation. Inch.	Ratio of bare diameter to thickness of insulation.	Weight of insulation per 100 lbs. of covered wire.	Weight of covered wire per lb. of bare wire, k_2.
1	..	.300	7.62	..	..	..	..	.020	15	2.28	1.022
..	1	.289	7.34	..	..	..	..	.020	14.45	2.32	1.023
..	..	.284	7.21	..	..	..	..	.020	14.2	2.33	1 023
..	..	.259	6.58	..	..	..	..	.020	12.95	2.40	1.024
..	2	.258	6.55	..	..	..	..	.020	12.9	2.40	1.024
4	..	.238	6.04	..	..	..	..	.020	11.9	2.50	1.025
..	3	.229	5.82	..	..	..	..	.020	11.45	2.55	1.025
5	..	.220	5.59	..	..	..	..	.020	11	2.65	1.026
..	4	.204	5.18	.012	17	2.20	1.022	.020	10.2	2.85	1.028
6	..	.203	5.16	012	16.9	2.20	1.022	.020	10.15	2.86	1.028
..	5	.182	4.62	.012	15.15	2.27	1 0227	.018	10.1	2.87	1.028
7	..	.180	4.57	.012	15	2.28	1.0228	.018	10	2.90	1.029
8	..	.165	4.19	.012	13.75	2.33	1 0233	.018	9 17	3.20	1.032
..	6	.162	4.12	.010	16.2	2.24	1 0224	.018	9	3.25	1.033
9	..	.148	3.76	.010	14.8	2.30	1.023	.016	9.25	3.15	1.031
..	7	.144	3.66	.010	14.4	2 32	1.0232	.016	9	3.25	1.033
10	..	.134	3.40	.010	13.4	2.36	1.0236	.016	8.4	3.55	1.035
..	8	.1285	3.27	.010	12.85	2.40	1.024	.016	8	3.75	1.0377
11	..	.120	3.05	.010	12	2.50	1.025	.016	7.5	4.10	1 041
..	9	.1144	2.91	.010	11.4	2.55	1.0255	.016	7.1	4.35	1 043
12	..	.109	2.77	.010	10.9	2.66	1.0266	.016	6 8	4.60	1.046
..	10	.102	2.59	.010	10.2	2.85	1.0285	.016	6.4	5.00	1.05
13	..	.095	2.41	.010	9.5	3.10	1.031	.016	5.9	5.55	1.052
..	11	.091	2.31	.010	9.1	3.25	1.0325	.016	5.7	5.85	1.058
14	..	.083	2.11	.007	12	2.50	1.025	.016	5.2	6.60	1.066
..	12	.081	2.06	.007	11.6	2.54	1.0254	.016	5.1	6.80	1.068
15	13	.072	1.83	.007	10.3	2.80	1.028	.016	4.5	7.80	1.078
16	..	.065	1.65	.007	9.3	3.15	1.0315	.016	4.1	8.60	1.086
..	14	.064	1.63	.007	9.1	3.25	1.0325	.016	4	8.80	1.088
17	..	.058	1.47	.007	8.3	3.60	1.036	.014	4 1	8.60	1.086
..	15	.057	1.45	.007	8.1	3.70	1.037	.014	4 1	8.60	1.086
..	16	.051	1.30	.007	7.3	4.20	1.042	.014	3.6	9 60	1.096
18	..	.049	1.25	.007	7	4.40	1.044	.014	3.5	9.80	1.098
..	17	.045	1.15	.005	9	3.25	1.0325	.012	3.75	9.30	1.093
19	..	.042	1.07	.005	8.4	3.55	1.0355	.012	3.5	9.80	1.098
..	18	.040	1.02	.005	8	3.75	1.0375	.012	3 33	10.10	1 101
..	19	.036	0.91	.005	7.2	4.30	1.043	.005*	7.2	5.60	1.056
20	..	035	0 89	.005	7	4.40	1.044	.005*	7	6.00	1.06
21	20	032	0.81	.005	6.4	5.00	1.05	.005*	6.4	6.60	1.066
22	21	028	0 71	.005	5.6	6.00	1 06	.004*	7	6.00	1.06
23	22	.025	0.64	.005	5	7.00	1.07	.004*	6.25	7.00	1 07
24	23	.022	0.56	.005	4.4	8.00	1.08	.004*	5.5	8.00	1 08
25	24	.020	0.51	.005	4	8.80	1.088	.004*	5	8.80	1.088
26	25	.018	0.46	.005	3.6	9.60	1.096	.004*	4.5	9.60	1.096
27	26	016	0.41	.005	3.2	10.40	1.104	.004*	4	10.40	1.104
28	27	.014	0.36	.005	2.8	11.25	1.1125	.004*	3.5	11.25	1.112
29	28	.013	0.33	.005	2 6	11.65	1.1165	.004*	3.25	11.65	1.116
30	..	.012	0.31	.005	2.4	12.05	1.1205	.004*	3	12.05	1.120
..	29	.011	0,28	.005	2.2	12.45	1.1245	.004*	2.75	12.45	1.124

* Double silk: 1 mil of silk insulation taken equal in weight to 1.25 mil of cotton covering.

Recommended by the Committee on Notation of the Chamber of Delegates of the International Electrical Congress of 1893.

With the names added in italics of the practical magnetic units provisionally adopted by the American Institute of Electrical Engineers.

Physical Quantities.	Symbols.	Defining Equations.	Dimensions of the Physical Quantities.	Names of the C. G. S. Units.	Practical Units.
Fundamental.					
Length	L, l	.....	L	Centimetre.	Metre.
Mass	M	.....	M	Mass of one gramme.	Mass of a kilogramme.
Time	T, t	.....	T	Second.	Minute; hour.
Geometric.					
Surface	S, s	$S = L.L$	L^2	Square centimetre.	Square metre.
Volume	V	$V = L.L.L$	L^3	Cubic centimetre.	Cubic metre.
Angle	α, β	$\alpha = \frac{\text{arc}}{\text{radius}}$	A number.	Radian.	Degree; minute; second; grade.
Mechanical.					
Velocity	v	$v = \frac{L}{T}$	LT^{-1}	Centimetre per second.	Metre per second.
Angular Velocity	ω	$\omega = \frac{v}{L}$	T^{-1}	Radian per second.	Revolutions (turns) per minute.
Acceleration	a	$a = \frac{v}{T}$	LT^{-2}	Centimetre per second per second.	Metre per second per second.
Force	F, f	$F = Ma$	LMT^{-2}	Dyne.	Gramme; kilogramme.
Work	W	$W = FL$	L^2MT^{-2}	Erg.	Kilogrammetre.
Power	P	$P = \frac{W}{T}$	L^2MT^{-3}	Erg per second.	Kilogrammetre per second.
Pressure	p	$p = \frac{F}{S}$	$L^{-1}MT^{-2}$	Dyne per square centimetre.	Kilogram per square centimetre.
Moment of Inertia	K	$K = ML^2$	L^2M	Gramme-mass-centimetre-squared.	
Magnetic.					
Strength of Pole	m	$F = \frac{m^2}{L^2}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$		
Magnetic Moment	$\mathfrak{M}$	$\mathfrak{M} = ml$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$		
Intensity of Magnetization	$\mathfrak{I}$	$\mathfrak{I} = \frac{\mathfrak{M}}{V}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$		
Field Intensity	$\mathfrak{H}$	$\mathfrak{H} = \frac{F}{m}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Flux of (Magnetic) Force	Φ	$\Phi = \mathfrak{B}S$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$	*Weber.*	*Weber.*
Magnetic Induction	$\mathfrak{B}$	$\mathfrak{B} = \mu\mathfrak{H}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Magnetizing Force‡	$\mathfrak{H}$	$\mathfrak{H} = \frac{4\pi NI}{L}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Magnetomotive Force	$\mathfrak{F}$	$\mathfrak{F} = 4\pi NI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$	*Gilbert.*	*Gilbert*; 1 *Gilbert* = 0.7958 ampère-turns (a-t).
Reluctance (Magnetic Resistance)	$\mathfrak{R}$	$\mathfrak{R} = \nu\frac{L}{S}$	L^{-1}	*Oersted.*	*Oersted.*
(Magnetic) Permeability	μ	$\mu = \frac{\mathfrak{B}}{\mathfrak{H}}$	A number.		
(Magnetic) Susceptibility	κ	$\kappa = \frac{\mathfrak{I}}{\mathfrak{H}}$	A number.		
Reluctivity (Specific Magnetic Resistance)	ν	$\nu = \frac{1}{\mu}$	A number.		
Electromagnetic.					
Resistance	R, r	$R = \frac{E}{I}$	LT^{-1}	.....	Ohm.
Electromotive Force	E, e	$E = RI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Volt.
Difference of Potential	U, u	$U = RI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Volt.
Intensity of Current	I, i	$I = \frac{E}{R}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Ampère.
Quantity of Electricity	Q, q	$Q = IT$	$L^{\frac{3}{2}}M^{\frac{1}{2}}$	.....	Coulomb; ampère-hour
Capacity	C, c	$C = \frac{Q}{E}$	$L^{-1}T^2$	.....	Farad.
Electric Energy	W	$W = EIT$	L^2MT^{-2}	.....	Joule; watt-hour.
Electric Power	P	$P = EI$	L^2MT^{-3}	.....	Watt; kilowatt.
Resistivity (Specific Resistance)	ρ	$\rho = \frac{RS}{L}$	L^2T^{-1}	.....	Ohm-centimetre.
Conductance	G, g	$G = \frac{1}{R}$	$L^{-1}T$	.....	Mho.
Conductivity (Specific Conductance)	γ	$\gamma = \frac{1}{\rho}$	$L^{-2}T$		
Coefficient of Induction (Inductance)	$\mathcal{L}, l$	$\mathcal{L} = \frac{\Phi}{I}$	L	.....	Henry.

‡N Is the number of windings, and L the length of the solenoid generating the magnetizing force.

TYPE "F. P." DOUBLE COMMUTATOR C & C MOTOR.

SECTION 5.

DIRECT CURRENT MOTORS.

GENERAL DISCUSSION.

It has been shown that by means of a **generator** mechanical energy is converted into the electrical form of energy. An electric **motor** is the reverse of this, that is, it converts electrical energy into the mechanical form of energy.

Fundamental Principle. We have learned that when a conductor which forms part of a circuit moves so as to cut lines of magnetic force, a current passes in the conductor, this being the principle of the generator. On the other hand, if a current of electricity passes through a conductor at right angles to lines of magnetic force, the conductor tends to move so as to cut them. This will be made clear by considering Fig. 1. The dots repre-

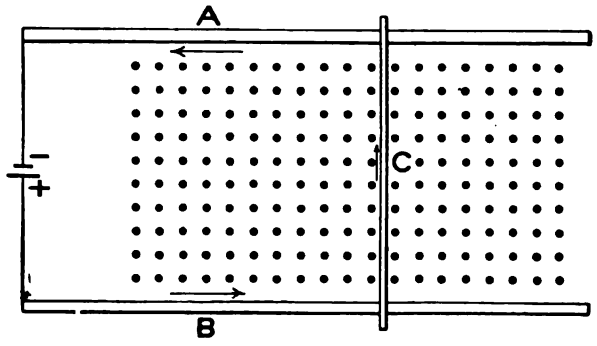


Fig. 1.

sent lines of magnetic force, their direction being upwards through the paper. *C* represents a conductor that is movable on the rails *A* and *B* which form part of the circuit. The current flowing through *C* causes it to move along the rails to the right or left according to the direction of the current. This is the fundamental principle of the motor.

Thus we have a means of imparting mechanical motion to a body at the expense of electrical energy.

Direction of Motion. A simple method of obtaining the direction of motion when the direction of the current and of the lines of force are known, is by means of Fleming's rule. In finding the direction of the current in generators the *right* hand is used. In finding the direction of motion of motors the *left* hand is used. The thumb, forefinger, and middle finger of the left hand are held at right angles to each other; then if the forefinger shows the direction of the lines of force, and the middle finger the direction of the current, the thumb will show the direction of motion.

By applying this rule to the case shown in Fig. 1 it appears that the motion of C will be to the right. If the current was in the opposite direction C would move to the left. If the direction of the lines of force was downward through the paper, the direction of current remaining as represented, C would move to the left. If both the direction of current and lines of force were opposite to that represented in Fig. 1, then by the rule it is evident that the motion of C will still be to the right.

Interchangeability of Motors and Dynamos. There is essentially no difference between a motor and a dynamo. In fact dynamos usually may be run as motors or motors may be run as dynamos. If a current is passed through the armature of a dynamo we have the conditions for a motor, and the armature will rapidly rotate.

In view of these facts it is evident that nearly all that has been said in regard to generators, applies equally well to motors. Therefore in this section it is only necessary to consider the special characteristics of the latter.

Motion of the Armature. Fig. 2 represents a ring armature which is supplied with a current of electricity from some external source. The direction of the lines of force of the field is from right to left. The direction of the current in a ring armature should be taken as that in the wire on the outside, because the wire on the outside of the ring cuts a greater number of lines of force than the wire on the inside of the ring. Nearly all lines pass through the armature core, as in Fig. 3.

Considering the right-hand half of the ring we see that the direction of the current in the winding on the outside is downward through the paper. By applying Fleming's rule, using the left

hand, it is seen that the rotation of the armature will be left-handed. Now considering the left-hand half of the ring (the current in the winding on the outside being upward through the paper) the rotation of the armature is found to be left-handed. Hence each half of the armature causes a left-handed rotation.

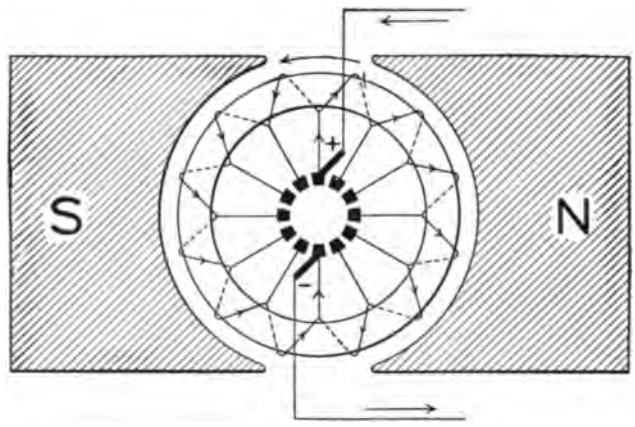


Fig. 2.

Reversal of Rotation. By reversing *either* the direction of the lines of force *or* the direction of the armature current, the direction of rotation will be reversed. If *both* the lines of force and the current are reversed the direction of rotation will be unchanged. These statements may be verified by the application of Fleming's rule to the different cases.

Therefore, the direction of rotation of a motor armature may be changed by reversing *either* the field of force *or* the armature current, but not both.

Generators Run as Motors. By applying Fleming's rule as to the direction of rotation of motors it is easy to determine in what direction the armature of a generator will rotate when run as a motor.

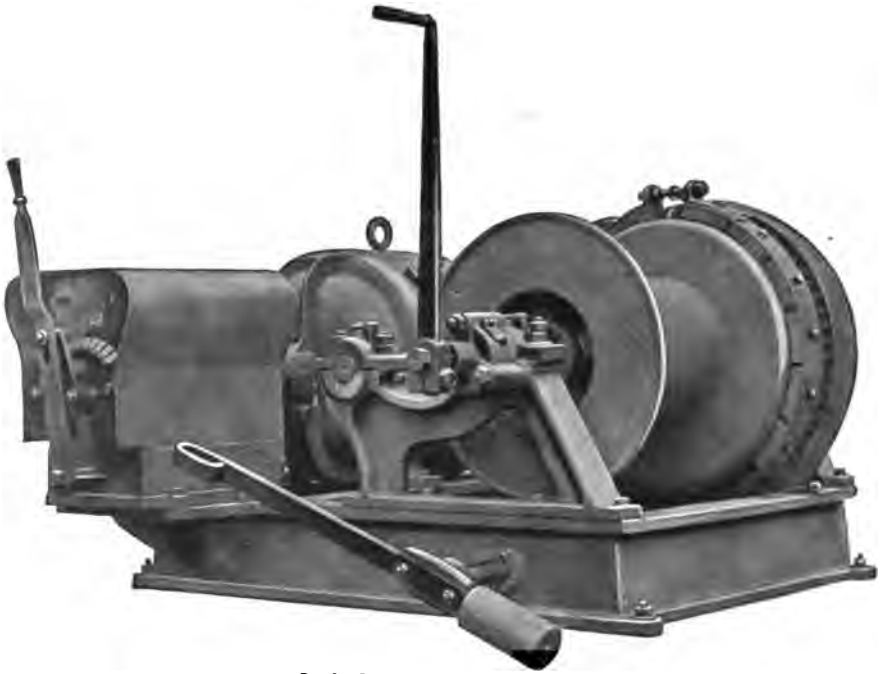
If a series generator is run as a motor the armature will rotate in the opposite direction to that in which it has been driven because both the armature and field currents are reversed; it is, therefore, necessary to reverse the brushes. If the original direction of rotation is desired then either the armature or field connections must be reversed.

The armature of a shunt generator will rotate in the same direction when run as a motor, because while the armature current is reversed the field current has the same direction as when run as a generator.

The armature of a compound generator will have its direction of rotation reversed when run as a motor if the series winding has a greater magnetizing effect than the shunt winding. The direction of rotation will remain the same if the magnetizing effect of the shunt coil is greater than that of the series winding. This will be understood when it is considered that in the generator the field excitation is that due to the *sum* of the magnetizing effects of the shunt and series coils, whereas when run as a motor it is their difference. Of course reversing the connections of either the series or shunt winding would then cause the field excitation to be that due to their sum, the direction of rotation depending upon which connections were changed. If the connections of the series coil were changed the direction of rotation would remain as before; changing the connections of the shunt coil would reverse the rotation.

Counter Electromotive Force. We have learned that when a conductor moves across lines of magnetic force, an E. M. F. is generated in the wire, and that this is the fundamental principle of the dynamo. Now, when the armature of a motor is caused to rotate, by passing a current through it, the very act of moving across the field of the motor causes the generation of an E. M. F. This E. M. F. is opposed to that applied to the motor and is known as the *counter* E. M. F.

The greater the speed of the armature, the greater will be this counter E. M. F., as a larger number of lines of force are cut in a given time. Also the greater the counter E. M. F. the less will be the drop of potential in the armature, for the effective E. M. F. is reduced as the counter E. M. F. increases. The strength of the armature current will therefore depend upon the speed. When the armature is forcibly restrained from rotating, the current is at its maximum, being equal to the E. M. F. applied at the brushes divided by the resistance. On releasing the armature, the strength of the current gradually decreases as the motor comes up to speed.



C & C ELECTRIC HOIST,
Equipped with "F. P. E." Motor.

Motor Equation. The drop of potential in a motor armature is equal to the applied E. M. F. minus the counter E. M. F. Hence from Ohm's law, we have,

$$I = \frac{E - e}{r}$$

where I is the armature current, E the E. M. F. applied at the brushes, e the counter E. M. F., and r the armature resistance. This is the fundamental *motor equation.*

From this equation it is evident that when e is small, that is, before the motor is up to speed, the armature current will be large. As the speed increases the counter E. M. F. is increased causing the current to become less and less until at full speed the current is normal.

Example. — The armature resistance of a motor is .54 ohm, the E. M. F. at the brushes is 215 volts, and the counter E. M. F. is 190 volts. What current passes through the armature?

Solution. — By the motor equation,

$$I = \frac{215 - 190}{.54} = 46.3 \text{ amperes (nearly).}$$

Ans. 46.3 amperes.

Example. — If the armature current is 14.1 amperes, the voltage at the brushes 109 and the armature resistance 1.69 ohms, what is the counter E. M. F.?

Solution. — Substituting in the motor equation,

$$14.1 = \frac{109 - e}{1.69}$$

$$e = 85.2 \text{ volts (approx.).}$$

Ans. 85.2 volts.

The Distortion of Field which occurs in a dynamo is also present in a motor, being due to the fact that the lines of force of the armature field are nearly at right angles to those of the field magnets, the amount of distortion being dependent upon the relative strength of the two fields.

In a motor the direction of the armature current and consequently the direction of its field is opposite to that in a dynamo. This causes the resultant field of a motor to be as represented in Fig. 3. It is evident that the neutral points are shifted *backwards*, whereas in the generator they are shifted forwards. This figure

should be compared with the corresponding one for a dynamo, Fig. 29, in the section devoted to *Theory of Dynamo-electric Machinery*. Hence, to place the brushes at the neutral point of a motor they are shifted in an opposite direction to that of rotation. The greater the armature current the greater will be the distortion of field, and the more the brushes must be shifted backwards.

If the field magnets are made very powerful as compared with the armature, the distortion of field will be very slight or will be practically absent. In that case the brushes need not be shifted for variations in the load.

As seen in Fig. 3 the density of the lines of force is greater at the horns A, which the armature is approaching, than at the horns *B*, from which it is receding; consequently the induced Foucault currents and the heating will be greater in the horns *A*,

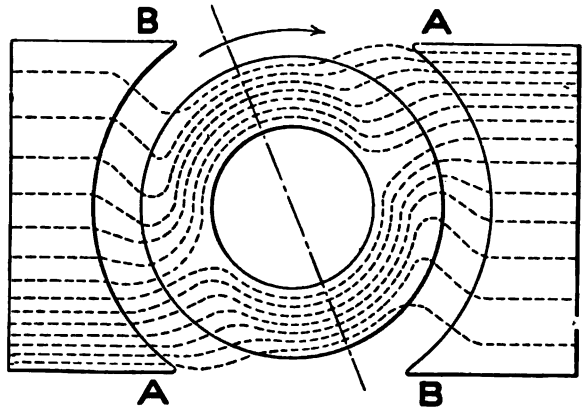


Fig. 3.

while in the generator the heating is greater in the horns from which the armature is receding. In the case of the motor the air current tends to equalize the difference of temperature between the horns *A* and *B*, because cool air is drawn in at *A* and ejected somewhat warmer, at *B*; whereas in the generator cool air is drawn in at the cooler horns which tends to increase the difference of temperature.

Efficiency. The *commercial efficiency* of a motor is equal to the actual output divided by the actual input, or

$$commercial\ efficiency = \frac{output}{input}.$$

Or $$\textit{commercial efficiency} = \frac{\textit{input} - \textit{losses}}{\textit{input.}}.$$

The losses in a motor may be given under two heads:

The **electrical** losses,

(a) Armature wire I^2 R loss.

(b) Field wire I^2 R loss.

The **stray power** losses,

(c) Friction of bearings.

(d) Friction of brushes.

(e) Friction due to air resistance.

(f) Waste currents in coils during commutation.

(g) Foucault currents in armature core.

(h) Hysteresis in armature core.

(i) Foucault currents in armature wire.

(j) Foucault currents in pole pieces.

The electrical losses in the field and armature windings are due to the heating of the conductors by the current flowing through them. This loss as we have learned varies directly as the square of the current and as the resistance, that is, as I^2R.

The stray power losses are small when considered separately, excepting friction of bearings, but collectively they usually amount to as much as the electrical losses. The stray power losses are practically constant for any load.

The *electrical efficiency* is the efficiency of the motor when only the electrical losses a and b are considered. This may be expressed as the input minus the electrical losses, divided by the input, or

$$\textit{electrical efficiency} = \frac{\textit{input} - \textit{electrical losses}}{\textit{input}}.$$

The electrical efficiency, therefore, only indicates the amount of the electrical losses and does not take into account the stray power losses.

The *efficiency of conversion* or *gross efficiency* of a motor is the ratio of the output to the useful electrical energy or to the input minus the electrical losses, that is,

$$\textit{gross efficiency} = \frac{\textit{output}}{\textit{input} - \textit{electrical losses}}.$$

The gross efficiency, therefore, takes into account only the stray power losses.

When no efficiency is specified, the commercial efficiency is understood.

The commercial efficiency of small motors ranges from 50% to 75%. Motors of from three to ten horse-power have efficiencies which range from 75% to 85 %. Larger motors should have an efficiency in the neighborhood of 90%.

Example.—A motor has at its terminals an E. M. F. of 220 volts, and takes a current of 26 amperes. The output is 5.94 horse-power; what is the efficiency of the motor?

Solution.—Input $= 220 \times 26 = 5720$ watts.

$$= \frac{5720}{746} = 7.67 \text{ H. P. (approx.)}$$

$$\text{Efficiency} = \frac{5.94}{7.67} = .774 + \text{ or } 77.4 + \%$$

Ans. 77.4 + %

Siemens' Law of Efficiency. This law is as follows: The efficiency of a motor is equal to the ratio of the counter E. M. F. to the applied E. M. F.

This law assumes that the only loss existing is that in the armature wires, or $I^2 r$, where I is the armature current and r the armature resistance. Hence it is assumed that there are no stray power losses, and also that we have a magneto motor.

The proof of the law is as follows:

$$\text{Efficiency} = \frac{input - losses}{input}.$$

$$\text{Input} = E\,I.$$

$$\text{Losses} = I^2 r.$$

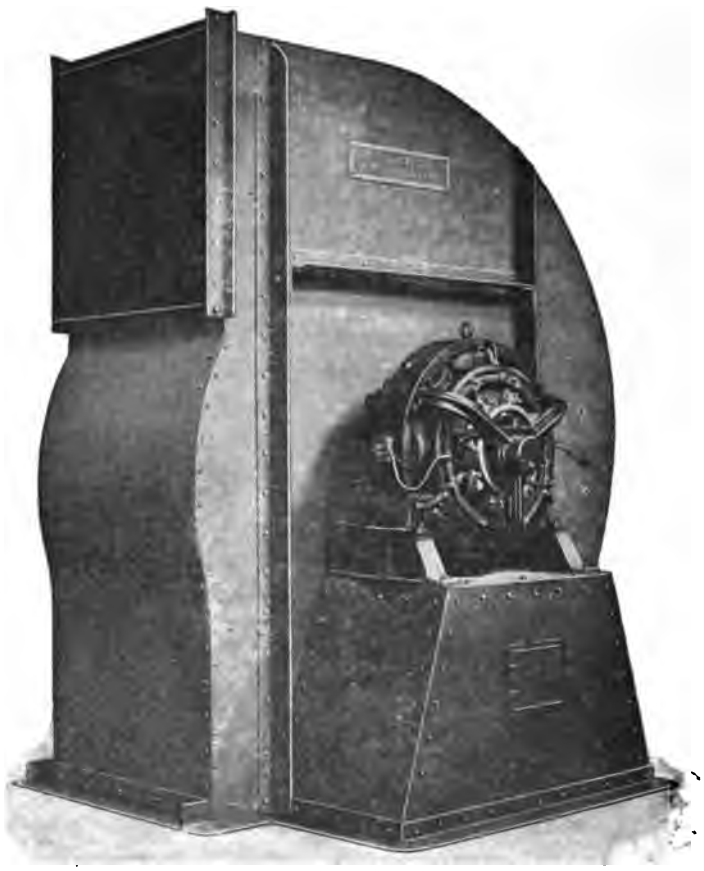
Hence,

$$\text{Efficiency} = \frac{E\,I - I^2 r}{E\,I}$$

$$= \frac{E - Ir}{E}$$

By the motor equation

$$I = \frac{E - e}{r}, \text{ then } Ir = E - e.$$



THE STURTEVANT STEEL PLATE ELECTRIC FAN.
8-Pole Motor, Circular Type.

Therefore,

$$\text{Efficiency} = \frac{E - (E - e)}{E}$$

$$\text{or, Efficiency} = \frac{e}{E}.$$

That is, the efficiency is equal to the counter E. M. F. divided by the applied E. M. F.

Hence the greater the counter E. M. F. the higher the efficiency of the motor. If the counter E. M. F. could become equal to the applied E. M. F., the efficiency would be equal to unity, or 100 per cent, but in that case no current would pass in the armature and consequently there could be no output.

Jacobi's Law of Maximum Output. This law may be stated as follows: The maximum amount of work is done by a motor when the speed is such that the counter E. M. F. is one-half of that applied to the motor.

The proof of this law is most easily understood by the aid of a diagram. Fig. 4 represents a square having the length of the side equal to E, the applied E. M. F. The distance A B is equal to e, the counter E. M. F. The diagonal is drawn from A, and the horizontal from B. At the point where this crosses the diagonal, a vertical is drawn. The distance B C is evidently equal to $E - e$.

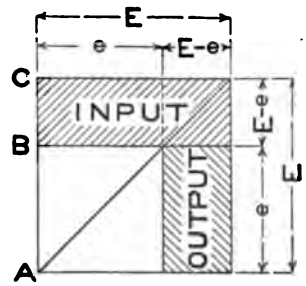


Fig. 4.

The input is equal to $E\,I$, and as

$$I = \frac{E - e}{r},$$

then

$$\text{input} = E\,I = \frac{E\,(E - e)}{r}.$$

The output is equal to the input minus the losses, that is,

$$\text{output} = \frac{E\,(E - e)}{r} - I^2\,r$$

$$= \frac{E\,(E - e)}{r} - \left\{\frac{E - e}{r}\right\}^2 r$$

$$= \frac{E\,(E - e) - (E - e)^2}{r}$$

$$= \frac{e\,(E - e)}{r}.$$

In these values of output and input a constant, r, appears in the denominator of each, therefore the relation of the output and input will be as the magnitude of the numerators. That is, we may represent output by $e\ (E - e)$, and input by $E\ (E - e)$. Referring to the figure, it is evident that the area of the rectangle *output* is equal to $e\ (E - e)$; that of the rectangle *input* is equal to $E\ (E - e)$.

Now if in Fig. 4 the counter E. M. F. is decreased the output will increase until it becomes a square, and will evidently then have a maximum value as shown in Fig. 5. The counter E. M. F. is then one-half the applied E. M. F. Hence the maximum amount of work is done by a motor when the counter E. M. F. is one-half of that applied.

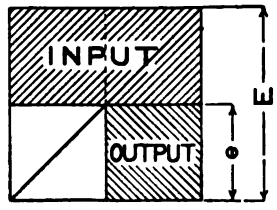


Fig. 5.

When a motor is doing a maximum amount of work the value of the current, as found by the motor equation, is one-half of that which would pass when the motor is at rest, that is, when no counter E. M. F. is generated.

It is evident from Fig. 5 that when the output is a maximum it is equal to one-half the input, consequently the efficiency is then 50%. This is also seen to be true from Siemens' law because e is one-half E, hence the efficiency is equal to 50%.

On account of the assumptions which must be made in the proof of these laws they are not strictly followed in practical machines.

Torque. The torque of a motor is its tendency to turn. It is usually expressed in pound-feet, and is equal to the pull in pounds exerted at one foot radius.

If it is known that a certain number of pounds pull is exerted at the circumference of a pulley whose radius is known, the torque is obtained by multiplying the pounds pull by the radius in feet. On the other hand, if the torque is known the pull at any radius is found by dividing by the radius.

The number of foot-pounds of work done by one revolution of a shaft is equal to the torque multiplied by $2\ \pi$, for $2\ \pi$ is the circumference in feet of a circle of one foot radius, and torque is the pounds pull at that distance, hence the product of the pounds

pull and distance through which it acts gives the work done. If there are n revolutions per minute, the foot-pounds of work done per minute will be $2\ \pi\ n\ T$, where T is the torque; hence the horse-power will be

$$\text{H. P.} = \frac{2\ \pi\ n\ T}{33{,}000}.$$

If the horse-power and number of revolutions are known, the torque may be found from the formula

$$T = \frac{\text{H. P.} \times 33{,}000}{2\ \pi\ n}.$$

If the torque and the horse-power are known, the number of revolutions may be found from the formula

$$n = \frac{\text{H. P.} \times 33{,}000}{2\ \pi\ T}.$$

In a given armature, the torque varies directly as the product of the field strength and armature current, or

$$T \textit{ varies as } f I$$

where T is the torque, f the field strength, and I the armature current. That is, if the field is kept constant the torque will vary directly as the armature current, and if the latter is kept constant the torque will vary directly as the field strength.

Measurement of Torque. The Prony brake may be used to measure the torque of a motor. The arrangement is shown in Fig. 6. P is a pulley on the armature shaft; the blocks A and C

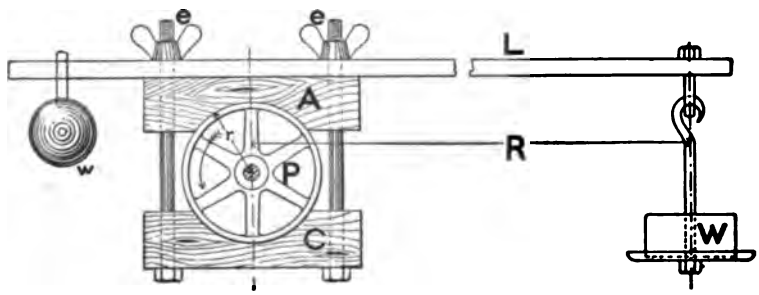


Fig. 6.

bear against the face of the pulley, the pressure being regulated by the wing-nuts e. The lever L which is clamped to A, is counterbalanced by the weight w. The weight W which is supported by

the lever has such a value as will keep the lever horizontal when the pulley is rotating.

To find the torque at a certain speed or when the motor take a certain current, the pressure on the pulley is adjusted until the speed or current is that desired. The weight W is made to balance the tendency of the lever to turn. The torque is then found by multiplying the measured distance R in feet, by the weight W in pounds.

Example.—In finding the output of a motor the distance R was 2.5 feet, the weight W was 12.4 pounds, and the number of revolutions of the motor was 1,400 per minute. What was the output of the motor in horse-power?

Solution.— Torque $= 2.5 \times 12.4 = 31.$ pound-feet.

$$\text{H. P.} = \frac{2\,\pi\,n\,T}{33{,}000}$$

$$= \frac{2 \times 3.142 \times 1{,}400 \times 31}{33{,}000}$$

$$= 8.25 + \qquad \text{Ans. } 8.25 + \text{H. P.}$$

Example.— What pull at the rim of a pulley 10 inches in diameter will be given by a 6 H. P. motor running 1,200 revolutions per minute?

Solution.— $$T = \frac{\text{H. P.} \times 33{,}000}{2\,\pi\,n}$$

In this case H. P. $= 6.$ $n = 1{,}200.$

Therefore

$$T = \frac{6 \times 33{,}000}{2 \times 3.142 \times 1{,}200} = 26.2 + \text{ pound-feet.}$$

But T = pounds pull × radius in feet.

= pounds pull × $\frac{5}{12}$

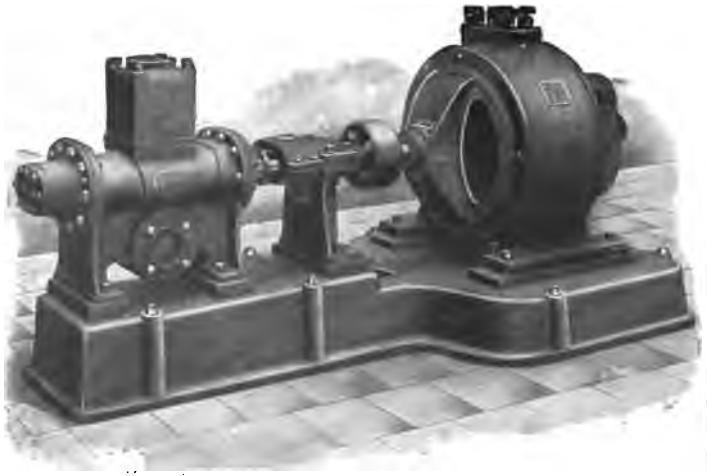
Therefore pounds pull $= 26.2 \times \frac{12}{5} = 62.7$ lbs. (approx.)

Ans. 62.7 lbs.

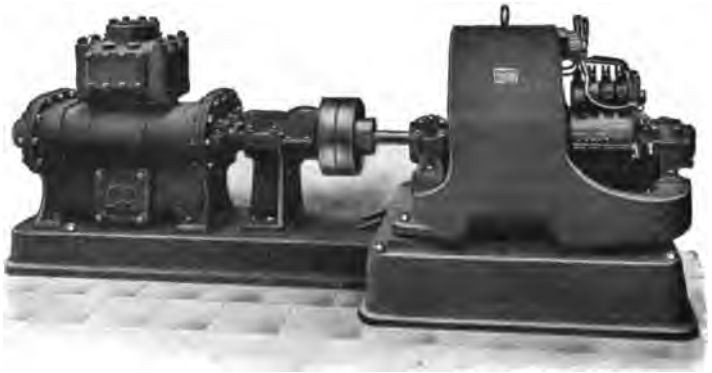
Speed. To arrive at a general expression which will show upon what factors the speed of a motor depends, we shall make use of the motor equation,

$$I = \frac{E - e}{r}.$$

Let s represent the speed of rotation, a the number of conductors on the surface of the armature, f the field strength, and k



Western Electric Motor, Direct Connected to a Quimby Pump.



A Western Electric Type K. K.-5 Motor Direct Connected to a Quimby Pump.

a constant. As the E. M. F. generated by an armature moving in a field depends upon the speed, number of conductors, and strength of field, the counter E. M. F. of a motor will be equal to

$$e = s\,a\,f\,k.$$

Substituting this value in the motor equation, we have

$$I = \frac{E - s\,a\,f\,k}{r} \quad \text{or} \quad I\,r = E - s\,a\,f\,k,$$

therefore $s\,a\,f\,k = E - I\,r$, and $s = \frac{E - I\,r}{a\,f\,k}$.

The armature resistance of a motor is usually very small, hence the product $I\,r$ would be small and may be neglected.

Therefore the expression for speed may be written

$$s = \frac{E}{a\,f\,k}.$$

From this expression it is evident that the speed varies *directly* as the E. M. F. applied at the brushes if the number of armature conductors and the field strength are constant. An increase in E causes a greater current to pass through the armature, which, acting upon the same field strength, causes an increase of speed, provided the torque exerted is kept constant.

If the number of armature conductors and the applied E. M. F. are constant, the above expression shows that the speed varies *inversely* as the field strength, that is, if the field is weakened the speed is increased or if the field is strengthened the speed is decreased. This is true for if the field is weakened the counter E. M. F. generated by the motor will be less allowing a greater current to pass in the armature. This will tend to increase the torque but if that is kept constant, the speed will increase, a higher speed being now required to generate the same E. M. F. as was the case when the field was stronger.

If the field strength and applied E. M. F. are constant, the speed varies *inversely* as the number of armature conductors, that is, a decrease in the number of armature conductors increases the speed. If a reduction is made in the number of conductors the motor must evidently run at a higher speed in order to generate the same counter E. M. F. as before, the torque being kept constant.

Windings of Motors. As in the case of a dynamo the common windings of a motor are shunt field winding, series field winding, and compound field winding.

The motor may be supplied with electrical power at a constant potential or the current may be constant.

SHUNT MOTORS ON CONSTANT POTENTIAL CIRCUITS.

Torque. As the torque of a motor with a given armature varies as the product of the armature current and field strength, if the field strength is constant the torque will vary directly as the strength of the armature current. The shunt motor on a constant potential circuit will have a constant current passing through the field coils, consequently the field strength will remain constant, and the torque will vary only as the strength of the armature current.

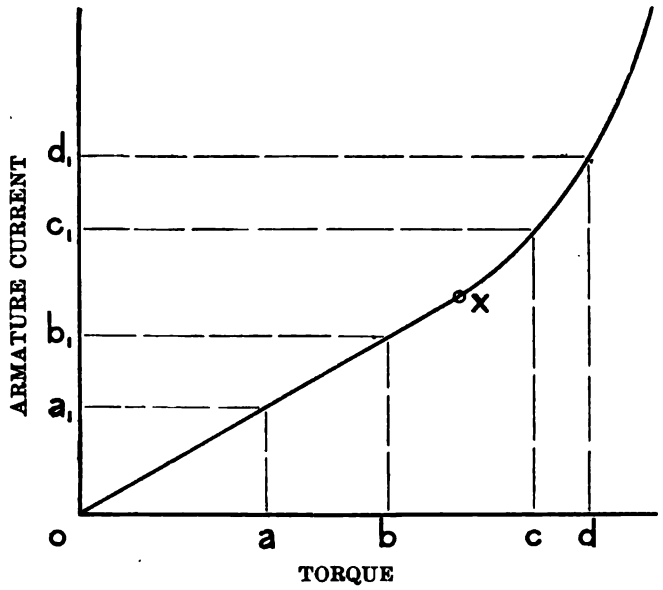


Fig. 7.

This is represented by the torque curve in Fig. 7. In this plot the abscissae *o a*, *o b*, *etc.*, represent the torque and the

ordinates $o\ a_1$, $o\ b_1$, *etc.*, the armature current, that is, when the torque has a value represented by $o\ a$ the corresponding value of the armature current will be $o\ a_1$. It is evident that from o to the point x the plot is a straight line, an increase in the armature current causing a proportional increase in the torque. Beyond point x the line is curved this being due to distortion of field by the large armature current. Here a considerable increase in the current as $c_1\ d_1$ produces but a small increase $c\ d$ in the torque. A good machine should not have much distortion of field at or under normal load.

Constant Speed. The speed of a shunt motor on a constant potential circuit is practically constant for any load.

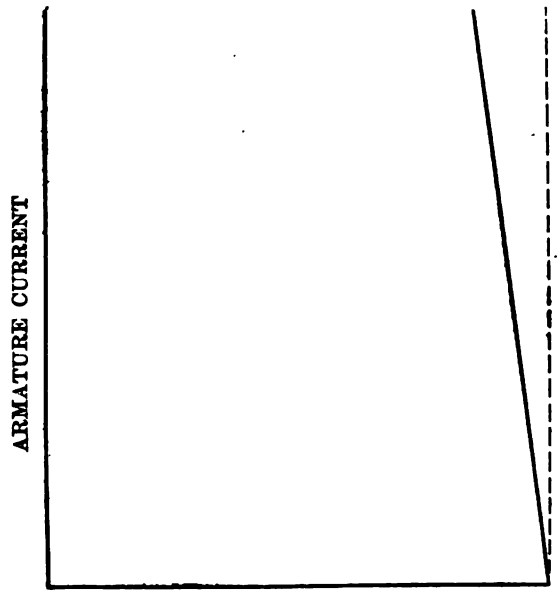


Fig. 8.

This is seen to be true from our approximate expression for speed,

$$s = \frac{E}{a f k}.$$

For since E is constant, f will be constant, and in a given armature a will be constant, therefore s will have a constant value.

As a matter of fact the speed will fall *slightly* as the torque increases. An increase of torque causes the armature current to be greater. As the applied E. M. F. is constant the increase in the armature current can only occur by decreasing the counter E. M. F., this being evident from the motor equation. Then if a decrease in the counter E. M. F. is necessary the speed must be slightly less.

This is represented in Fig. 8, which shows a gradually falling speed as the armature current is increased. In the figure, as indicated, the abscissae represent the speed, and the ordinates the armature current.

There are many methods of varying the speed of a shunt motor, all of which depend upon the variation of E. M. F. applied at the brushes, variation of field strength, or variation in the number of armature conductors. We will consider these methods in detail.

Variation of E. M. F. at the Brushes. We have seen that the speed of a motor varies directly as the E. M. F. applied at the brushes.

If a resistance is connected in series with the armature there will be a certain number of volts lost by the armature current passing through this resistance, consequently the voltage at the brushes will be less and the speed decreased. This method is illustrated in Fig. 9, the resistance R being inserted in the armature circuit. The commutator is represented by C, and the shunt field windings by F. The greater the resistance inserted the less will be the speed.

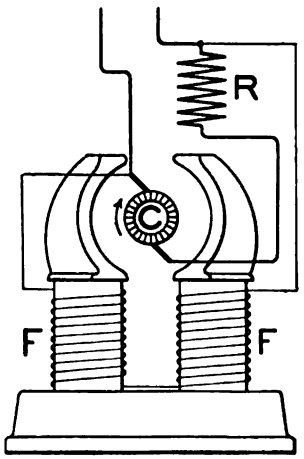
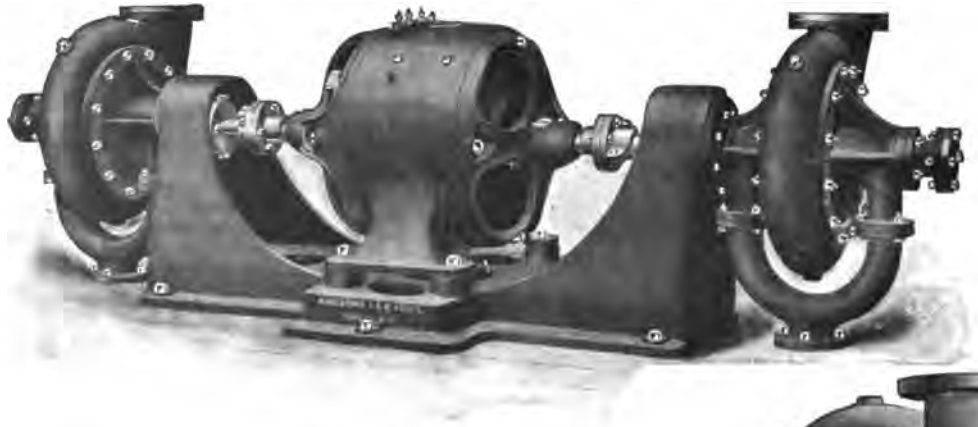
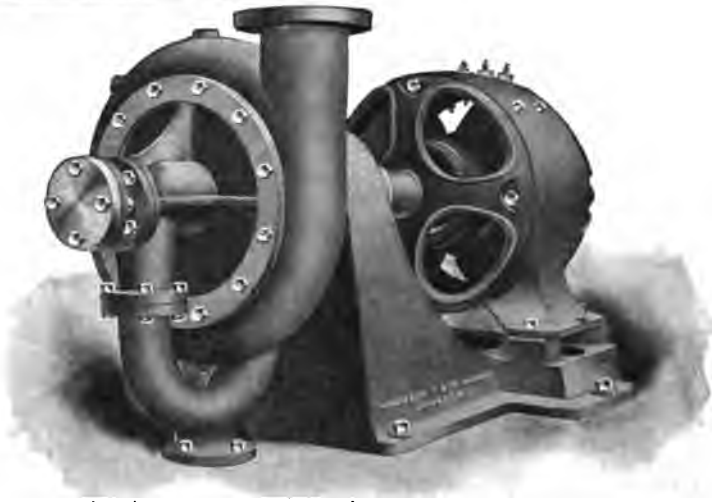


Fig. 9.

Problem. — Suppose a shunt motor is to be used on a 220 volt circuit, the current taken by the armature at full load being 16 amperes and the speed 1,000 revolutions per minute. It is desired that the motor should run at $\frac{1}{2}$ speed when the torque is $\frac{3}{4}$ of that at full load. What resistance R, is it then necessary to insert in the armature circuit?



Tailings and Slimes Pumps, Motor-Driven. (Patented.)



Special Motor-Driven Tailings Pump. (Patented.)

Solution. — Here $E = 220$, the normal current $I = 16$, and the speed $s = 1{,}000$ revolutions per minute.

We have seen that the expression for the speed of a motor is

$$s = \frac{E - Ir}{afk},$$

and, as only the voltage E is to be varied, the denominator afk is a constant. Hence the formula may be written

$$s = \frac{E - Ir}{\text{constant}}.$$

As the resistance R is in series with r, and as r is very small we can neglect it. With R inserted the formula becomes

$$s = \frac{E - IR}{\text{constant}}.$$

The value of the denominator is easily found, for, when R is cut out of the circuit, $IR = 0$, and the speed is normal being 1,000 revolutions. Substituting these values in the equation we have

$$1{,}000 = \frac{220 - 0}{\text{constant}}$$

$$\text{constant} = .220.$$

Hence

$$s = \frac{E - IR}{.220}.$$

The torque is to be $\frac{3}{4}$ of that at full load, and as the field strength is constant the torque is decreased by decreasing the armature current I. Hence at $\frac{3}{4}$ torque the current will be $\frac{3}{4}$ of that at full load or $\frac{3}{4} \times 16 = 12$ amperes. The speed is to be $\frac{1}{2} \times 1000 = 500$ revolutions per minute.

Substituting these values in the preceding equation we obtain

$$500 = \frac{220 - 12R}{.220}.$$

Therefore $R = 9.17$ ohms nearly.

Ans. 9.17 ohms.

The above method of regulating the speed of a shunt motor is the one most largely used, being simple and perfectly controlling

the speed at all loads. It has the disadvantage, however, of poor economy, because the energy lost as heat in the resistance is considerable, being equal to I^2R.

The resistance used for starting the motor (see page 24) must not be used for regulating the speed in the above way. The starting resistance is usually very compact, and has a relatively small surface exposed to the air. It does not heat much during the short time required for starting, but if allowed to carry the armature current continuously it is liable to burn out. Regulating resistances are often made of zigzag strips of iron, insulated with asbestos, and exposed as much as possible to the air.

Variations of Field Strength. It has been shown that an increase in the speed of a motor is obtained by weakening the field strength, and that a decreased speed is obtained by increasing the field strength.

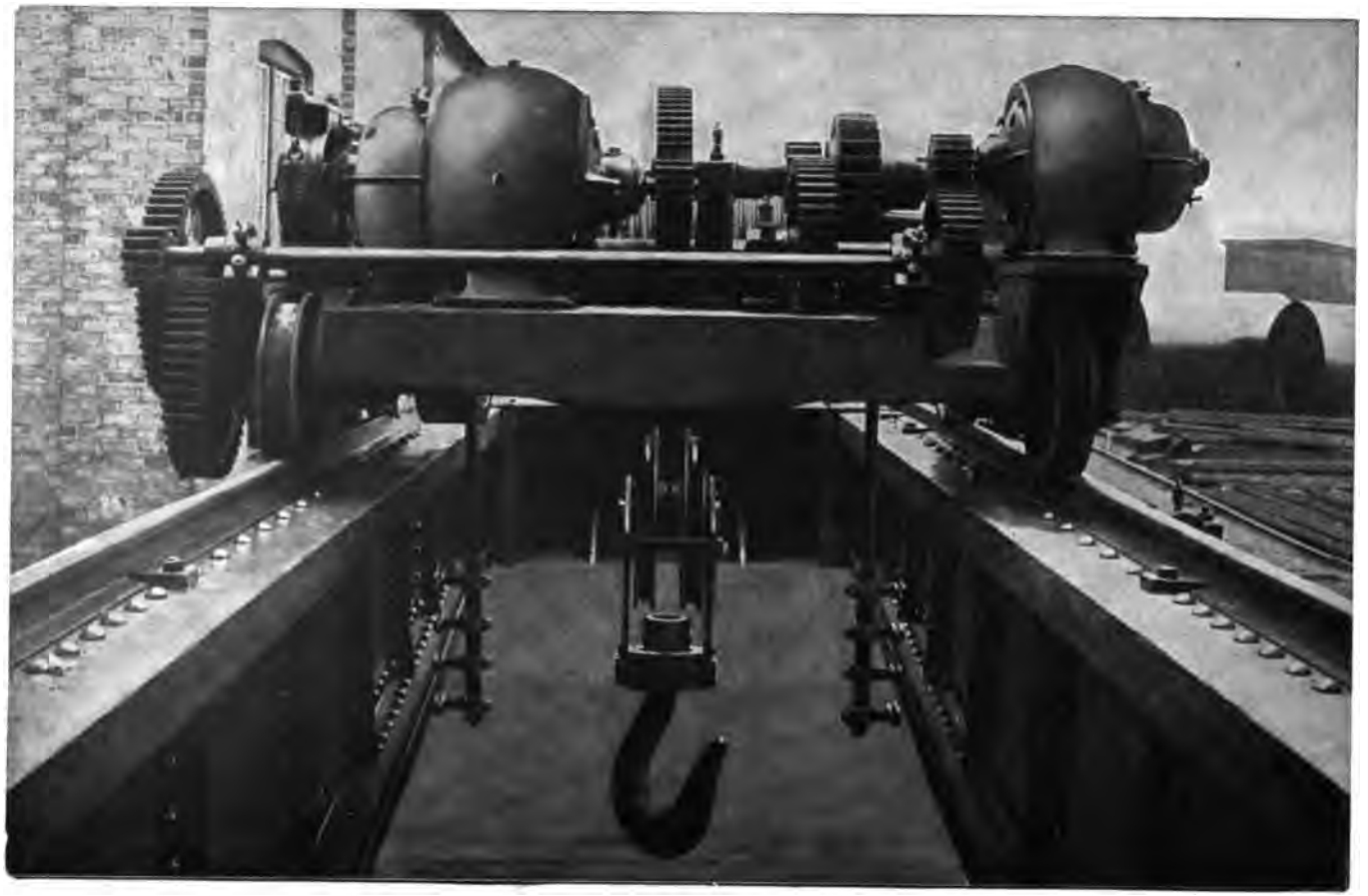
A simple and much used method of varying the field strength is the insertion or cutting out of resistance in the field circuit. This will change the current passing in the field coils and consequently the magnetization of the field magnets.

Another method of changing the magnetizing force is by having part of the field windings of German silver, and by cutting them in or out, the field strength is varied. As German silver has a high resistance the addition of these coils increases the resistance in greater proportion than the number of turns, so decreasing the ampere-turns. This method allows a moderate variation in speed, is easily operated, and is not expensive.

The objections to any method of regulating the speed by varying the field strength are:

1. If the speed is decreased the torque remaining constant, the motor gives out less power but requires at the same time an increased expenditure of energy in the fields.

2. It is customary in order to get the full power of a motor, to have the field magnets at or near the point of saturation at normal speed. But if it is desired to run the motor at a slower speed, the fields must be below their point of saturation at normal speed, since to decrease the speed the field strength must be increased. Hence at normal speed the fields are not worked to their full capacity, and the full power of the motor is not utilized. That



Electrically Operated Crane.
Courtesy of the Northern Electric Company.

is, the motor is larger than it otherwise would be, which means additional expense.

3. When the fields are weakened to increase the speed, the armature current causes greater distortion of the field and sparking is greatly increased.

If the resistance of the magnetic circuit is varied, the field strength will also be changed, and an increase of the magnetic resistance will cause an increase in the speed. This method of controlling the speed is not only usually difficult to apply but is also uneconomical. The magnetic resistance can be varied in three different ways: (*a*) the lines of force passing through the armature can be diverted through a movable piece of iron placed near the pole pieces, (*b*) the length of the air gap can be varied by having the relative position of field magnets altered, and (*c*) the cross section of the air gap can be varied by changing the relative position of the armature and pole pieces.

Variation of Number of Armature Wires. We have seen that the speed may be expressed approximately

$$s = \frac{E}{afk}.$$

If the armature is arranged so that every two wires can be connected in multiple the number of conductors will then be equivalent to $\frac{a}{2}$ having $\frac{1}{2}$ the resistance. This change will cause the new speed s' to be double the speed s. For

$$s' = \frac{E}{\frac{a}{2}fk} = \frac{2E}{afk},$$

which is twice the value of s.

If every two wires are again connected in multiple the number of conductors is $\frac{a}{4}$, the speed then being 4 s.

The same result is obtained in practice by changing two or more independent windings from series to multiple. These windings may be on the same armature core, or on separate cores on the same shaft, each winding requiring a separate pair of brushes.

The same result may be obtained by coupling separate motors to the same work.

Fig. 10 represents the changes where there are four independent armature windings or four independent motors. The separate commutators are represented by *c*, and field windings by *f*, the connections of the latter being the same for all speeds. In case *A* the brushes, and hence the armature windings are connected in series.

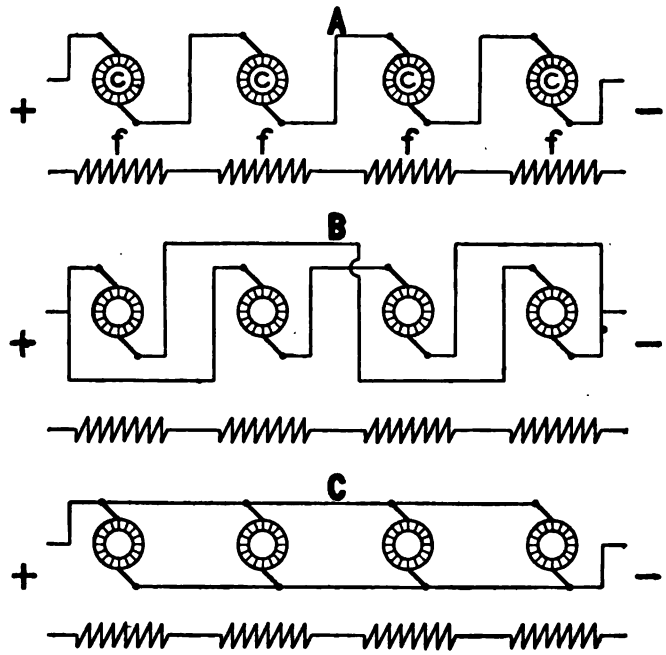


Fig. 10.

The number of armature windings being large the speed is small. In case *B* the armatures are connected in series multiple. The number of windings being then equivalent to $\frac{1}{2}$ of the number in the first case, the speed will be twice as great. In case *C*, the windings are all connected in multiple, hence the speed will be four times that in case *A*, and twice that in case *B*. We have, therefore, in case *C* full speed, in case *B* $\frac{1}{2}$ speed, and in case *A* $\frac{1}{4}$ speed.

This method of regulating the speed is satisfactory in regard to efficiency, for, if a constant torque is exerted by the motors

throughout the above changes, the current taken by each motor will have a constant value. Hence in case *B* the current used will be twice that in case *A*; but in the former case the speed is twice as great, and although the energy consumed is twice as much, the output is also double. Therefore the efficiency remains unchanged. Similarly the efficiency remains unchanged in case *C*.

The objection to this method is, of course, the use of several motors, which involves extra expense.

Variation of Position of the Brushes. By shifting the brushes from the neutral point the speed of the motor can be increased. This will be understood from Fig. 11.

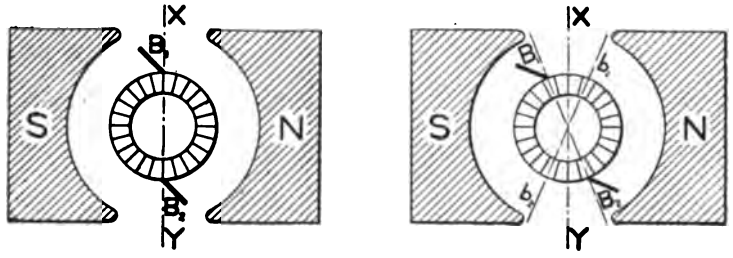


Fig. 11.

The neutral line is represented by *X Y*, and in the left-hand figure the brushes B_1 B_2 are at the neutral point, the entire counter E. M. F. generated, that is, by the conductors from B_1 to B_2, being effective. In the right-hand figure the brushes are shown shifted and in this position the effective counter E. M. F. is reduced. In this case the counter E. M. F. generated by the conductors from B_1 to *X* opposes that generated from *X* to B_2, the effective counter E. M. F. being reduced to that generated by the conductors from b_1 to B_2, and likewise from b_2 to B_1. For constant torque, however, the armature current must be constant when the field strength is not changed, therefore the counter E. M. F. must not be reduced. As a smaller number of conductors are now available to generate the counter E. M. F., the speed of the motor must be increased. That is, by shifting the brushes from the neutral point the speed is made higher.

This method is really equivalent to reducing the number of armature conductors. It has the great objection of causing exces-

sivesparking and of being injurious to the commutator, brushes, and armature winding.

Starting Resistance. If a motor armature is restrained from rotating the current passing through it will be very large, being equal to $\frac{E}{r}$, since no counter E. M. F. is generated. This excessive current would damage the armature, hence it is necessary to have a large resistance in the armature circuit to make the current small while the motor is coming up to speed. That is, before starting a motor, a large resistance should be connected in the armature circuit which is gradually reduced as the motor comes up to speed.

In order not to have the armature current in starting larger than the normal current, the resistance inserted, R, should be $R=\frac{E}{I}$, where E is the applied E. M. F. and I the normal armature current. For motors of more than 15 horse-power, however, R should be greater than $\frac{E}{I}$ in order not to throw a heavy load suddenly on the driving dynamo.

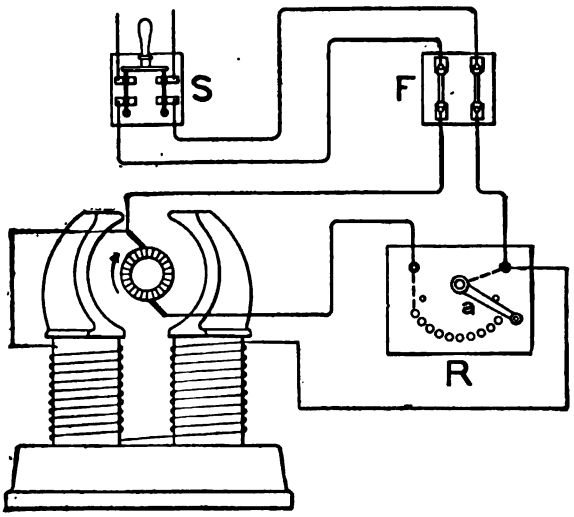


Fig. 12.

Connections. The connections for a shunt motor on constant potential mains are shown in Fig. 12. From the mains the con-

ductors lead to the double pole switch *S*. The fuses *F*, made of an easily fusible metal, are placed on both lines to protect the motor from dangerous currents caused by short circuits. The fuses are of such a cross section that they melt when a current greater than the safe one for the motor passes through them, and so break the circuit. The starting resistance is *R*, and is arranged so that turning the arm *a* will close the armature circuit inserting the full resistance *R*, and then gradually reduce it until it is all cut out. The switch *S* is placed outside the other connections so that when it is opened they are entirely disconnected and may be handled without fear of receiving a shock.

Starting. After making sure that the arm of the starting resistance is in the position so that the armature circuit is disconnected, the switch *S* is closed, and the fields then become fully charged before any current flows through the armature. The armature circuit is then closed through the resistance *R*, and as the motor speeds up this resistance is gradually cut out. As the speed of the motor increases, the counter E. M. F. becomes greater and the armature current less, allowing the resistance *R* to be cut out.

Stopping. In stopping the motor the switch *S* is first thrown. After the motor has come to rest the arm *a* of the resistance is then turned to the position ready for starting.

While coming to rest the motor runs as a generator and the field current is supplied by the armature. The direction of this current being the same as before, its strength will *gradually* decrease as the motor slows down, thus allowing a *gradual* decrease in the field strength.

If the armature circuit is broken first, then on throwing the switch *S* the field current is cut off abruptly, and the large current caused by self-induction produces a destructive flash at the switch; moreover a very high potential is produced in the field winding and this is likely to pierce the insulation. Also for this reason the switch should not be thrown unless the motor is afterwards started.

Reversing Motors. Motors are reversed in the direction of their rotation by simply changing the relative direction of the magnetic field and the armature current. This, as we have seen

is accomplished by changing *either* the direction of the armature current *or* the field current. The former is the more common method. A motor which is to be often reversed should have powerful field magnets so that there will be practically no distortion of the field, and no lead will be necessary for the brushes. Otherwise the lead would have to be changed when the rotation is reversed.

Reversing While Running. If the direction of the armature current is reversed while the motor is running, then until the armature comes to a stop and its rotation reversed, the counter E. M. F. acts *with* the applied E. M. F. This would cause the armature current to be extremely large being equal to

$$I = \frac{E + e}{r}.$$

It is therefore necessary that a large resistance R should be inserted in the armature circuit before the current is reversed. Then before the armature stops rotating the current will be

$$I = \frac{E + e}{R + r}.$$

However, as the direction of the armature current is now changed and comparatively large, the armature is quickly brought to rest, the current gradually decreasing as e becomes less and less.

When e becomes zero, that is, when the motor has stopped,

$$I = \frac{E}{R + r}.$$

The motor now speeds up in the opposite direction, e gradually increasing but now opposing E. As the motor speeds up, R is cut out, and the current becomes normal being equal to

$$I = \frac{E - e}{r}.$$

Reversing the direction of the current in the field circuit does not produce so abrupt a change in the motion of the armature, nor does its current become so excessively large. This is so because the field strength does not rise rapidly on account of self-induction and reluctance of the magnetic circuit; the armature then has time to slow down considerably so that the additive e is small, and the current cannot become as large as in the previous case.

The reversing of the field circuit however, causes severe sparking at the switch contacts as well as being likely to injure the field wire insulation.

A motor should never be reversed while running unless in the most necessary cases, and then not without inserting in the armature circuit the full resistance.

Reversing Connections. In Fig. 13 is shown a common form of reversing switch. The two metal bars H are pivoted one at a, and one at b. A strip K of insulating material joins the two

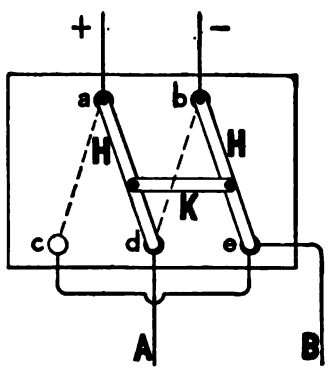


Fig. 13.

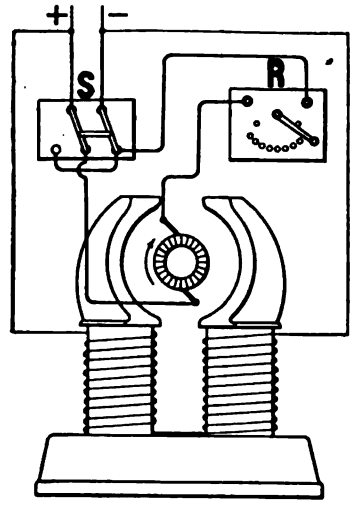


Fig. 14.

bars. In the position shown the wire A is positive and B is negative. When the bars are switched to contacts c and d in the position indicated by the dotted lines, wire B then becomes positive and A negative.

Fig. 14 shows the connections when a reversing switch S is inserted in the armature circuit of a shunt dynamo, the starting resistance being R. The reversing switch is sometimes combined with the starting resistance.

Maximum Output of Shunt Motor. We have seen that the maximum output of a motor when the only loss considered is that in the armature wires, is obtained when the armature current is $I = \frac{1}{2}\frac{E}{r}$; that is, when the strength of the current is one-half

of that which would flow if the armature was restrained from rotating, the counter E. M. F. being equal to $\frac{1}{2} E$.

Since the stray power and field wire loss for a shunt motor on a constant potential circuit are approximately constant for any load, the loss in the armature winding is the only variable loss. For this reason Jacobi's law is also true for the commercial shunt motor.

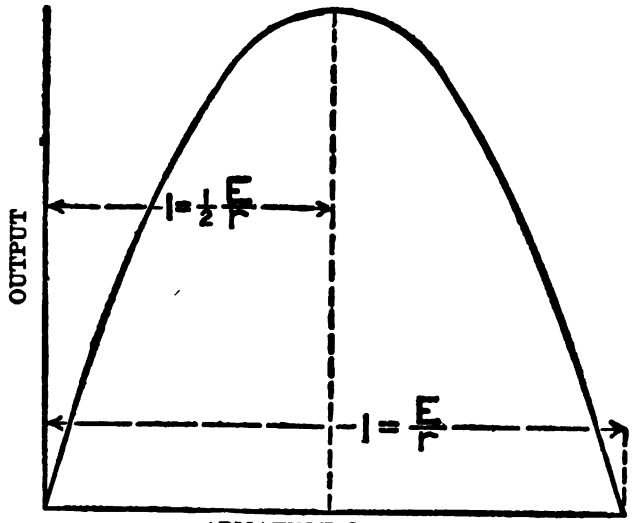


Fig. 15.

Fig. 15 shows the variation of the output with the armature current. At the beginning of the curve the current is zero, hence there could be no output. When the output has risen to its highest value, then $I = \frac{1}{2}\frac{E}{r}$ and $e = \frac{1}{2} E$. With a further increase in the current the output decreases until when $I = \frac{E}{r}$ the counter E. M. F. must be zero, that is; the motor is at rest and the output is zero.

Efficiency. Siemens' law of efficiency, $\left\{ \text{efficiency} = \frac{e}{E} \right\}$ is not closely followed by the commercial motor, since when the stray power and field wire loss is also taken into account, the efficiency will evidently be less than $\frac{e}{E}$.

It can be shown mathematically that the commercial efficiency of a shunt motor will be a maximum when the armature current has such a value that its square is equal to

$$\frac{\text{field wire loss} + \text{stray power loss,}}{\text{armature resistance}}$$

$$\text{or} \qquad I^2 = \frac{i_1^2 r_1 + S.P.}{r}$$

where i_1 is the field current and r_1 the resistance of the field winding.

The variation of the commercial efficiency of a shunt motor

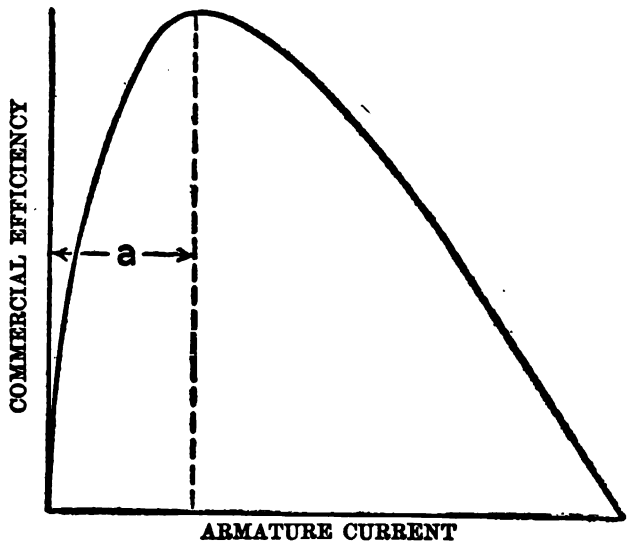


Fig. 16.

with a change in the armature current is shown in Fig. 16. It is seen that the efficiency rapidly rises with an increase in the current to its maximum value, and decreases more slowly as the current is further increased. When the efficiency is a maximum, the value of the current indicated by a in the figure is equal to

$$\sqrt{\frac{\text{field loss} + \text{stray power}}{\text{armature resistance}}}.$$

Advantage and Disadvantages of Shunt Motors. The great advantage of shunt motors is that their speed is practically constant.

The disadvantages are as follows:

1. The torque increases only in proportion to the armature current since the field strength is constant.

2. There is a high potential between the terminals of the field winding.

3. Opening the field circuit suddenly, causes a large spark and a high potential due to self-induction.

4. The many turns of fine wire of the field coils involve extra expense since fine wire costs more per pound than coarse, the labor of winding is considerable, and a large amount of insulation is necessary.

5. Where shunt motors are run intermittently it is customary to keep the field coils constantly charged, the motor being started and stopped by closing and opening the armature circuit through the resistance. Keeping the fields charged when the motor is not in use is of course a loss of energy.

Uses of Shunt Motors. A constant speed is of the greatest importance in some classes of work, and this advantage makes the use of shunt motors very extended.

Shunt motors are used in machine shops, factories, and to run printing presses, pumps, elevators, etc., or in general where good speed regulation is required.

SERIES MOTORS ON CONSTANT POTENTIAL CIRCUITS.

Torque. In the series motor the same current passes successively through the armature and field windings. We have seen that the torque depends upon the armature current and the field strength, or

$$T \text{ varies as } I f.$$

An increase in the current strength of a series motor greatly increases the torque because (*a*) the armature current is increased, and (*b*) the field strength is also increased by the larger field current. Hence in series motors the torque increases as the square of the current. Therefore on light loads the current is small and the

torque is small, and on heavy loads the current being large, the torque exerted is large. The torque increases as the square of the current, however, only when the fields are below their point of saturation. When near this point an increase in the current produces but a slight increase in the field strength, and the torque will then vary as the current strength only.

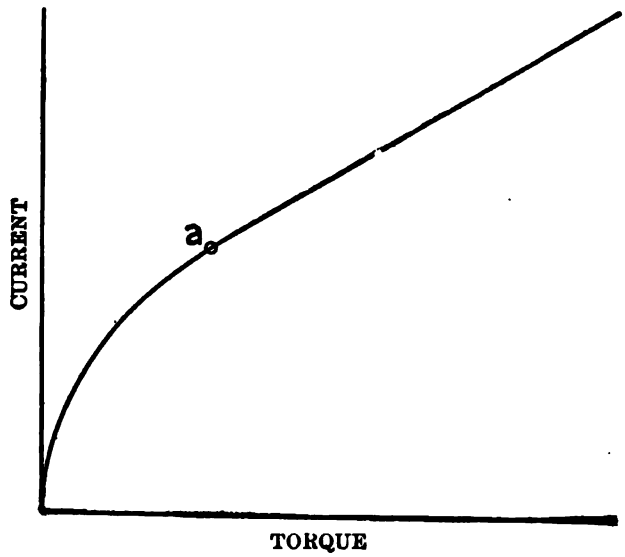


Fig. 17.

The curve in Fig. 17 shows the relation between the current taken by a series motor and the torque. Up to the point *a* the line has a considerable curve because the fields being below saturation, the torque increases as the square of the current. Beyond point *a* the fields are saturated and the torque then varies as the current only, the curve becoming a straight line.

Speed. In the case of shunt motors it was seen that the speed is nearly constant for all loads. In series motors the speed varies with the load. If part of the load is taken off of a series motor, the current becomes less, the fields are weakened, and this causes a large increase in the speed. If the load is entirely removed the speed becomes dangerously high.

Fig. 18 shows the speed curve for a series motor. It is evident from this curve that with a small current, or light torque on the motor, the speed is very large; with a large current the speed is small.

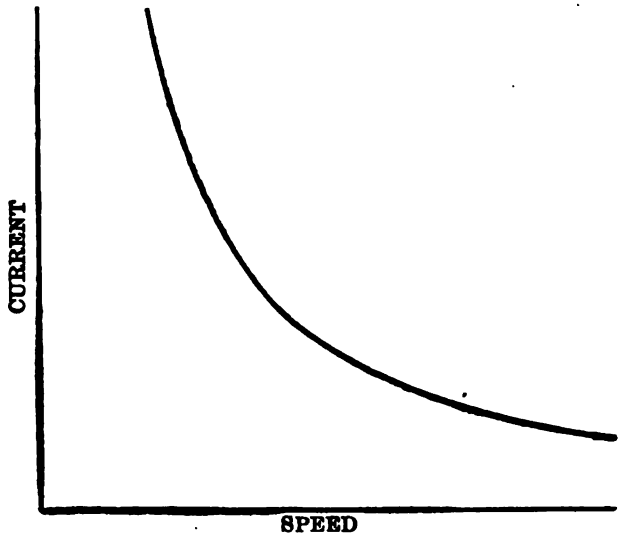


Fig. 18.

Speed Control of Series Motors. Series motors on constant potential circuits may have their speed controlled in a similar manner to that of shunt motors, there being some differences however, on account of the different field winding.

Variation of E. M. F. at the Brushes. This is the most common and most satisfactory method of controlling the speed. Fig. 19 illustrates this method, the resistance R being inserted to reduce the voltage available at the brushes, and consequently the speed. The current passes successively through the adjustable resistance R, the armature, and the field winding.

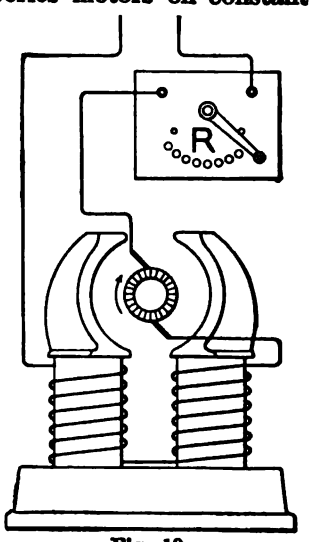


Fig. 19.

Variation of Field Strength. The field strength can be varied in several ways. If the field winding

is changed from a series coil to several coils in multiple the number of ampere-turns, and hence the magnetization will be reduced, causing the speed to be increased. Also cutting out turns or shunting a part of the field current through a by-path having an adjustable resistance will cause the speed to be increased. The latter method cannot be used for shunt motors, since the field winding is itself a shunt across the main circuit; but for series motors this method is a very useful one.

The resistance of the magnetic circuit may be varied as in shunt motors but this method is little used.

Other Methods. As in the case of shunt motors the speed of series motors may be varied by a change in the number of armature wires, as by coupling in series or multiple, and also by varying the position of the brushes. To obtain a very large range of speed there may be combinations of two or more methods.

Constant Speed. Nearly constant speed with varying load can be obtained with series motors by overwinding the field coils, that is, they may be wound so that the fields have their full strength when only one-half or even one-third of the normal current is passing. Hence with perhaps one-third load or more the fields will have a constant strength and the speed will be constant as in the case of the shunt motor. At full load the field current will be far greater than is necessary to saturate the magnets and consequently the efficiency is considerably lessened.

Starting. On starting, a rush of current tends to occur with this type of motor similar to that in case of the shunt motor; it is somewhat less however, because the field coils are in series with the armature and their resistance and self-induction reduce the excessive flow. A starting resistance is used as in the shunt motor, but can be considerably less.

Connections. These are very simple for a series motor and are indicated except the main switch and fuses, in Fig. 19; the same current passing successively through the starting resistance, armature and field winding.

Motors having more than two poles sometimes seem to have very complicated connections. Fig. 20 represents the connections for a four-pole series motor, and Fig. 21 for a four-pole shunt mo-

tor. By tracing out the connections the figures will be readily understood.

Reversing Series Motors. What has been said in regard to reversing shunt motors applies in general to series motors on constant potential circuits. Reversing while running is not so harmful to the latter as they are brought to rest sooner, since the excessive current passing through the field coils increases the field strength.

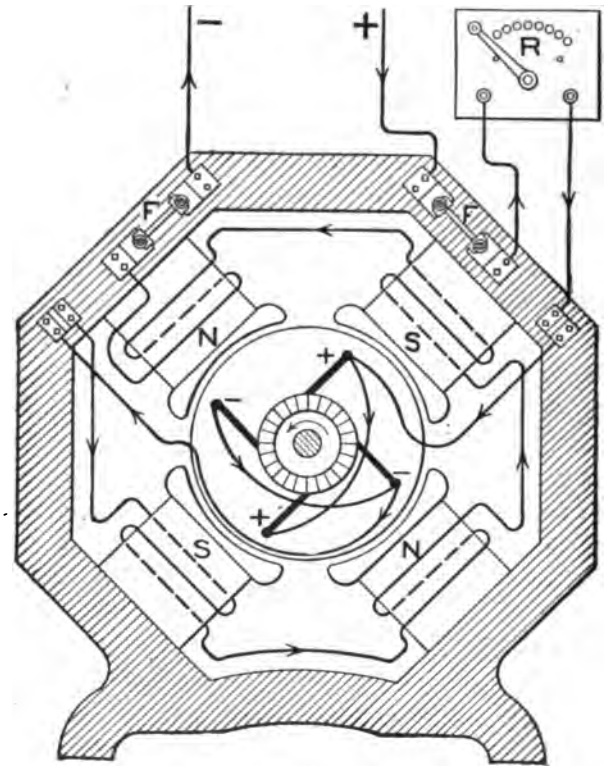


Fig. 20.

Advantages and Disadvantages of Series Motors. The advantages are:

1. The torque on overload is large; series motors are therefore well adapted for starting loads with great friction of repose.

2. The cost of the field coils is considerably less than in the

case of shunt motors as the number of turns required is very much less.

3. The field coils and armature being in series one switch serves to cut out both at once.

The disadvantages are:

1. The speed varies with the load.

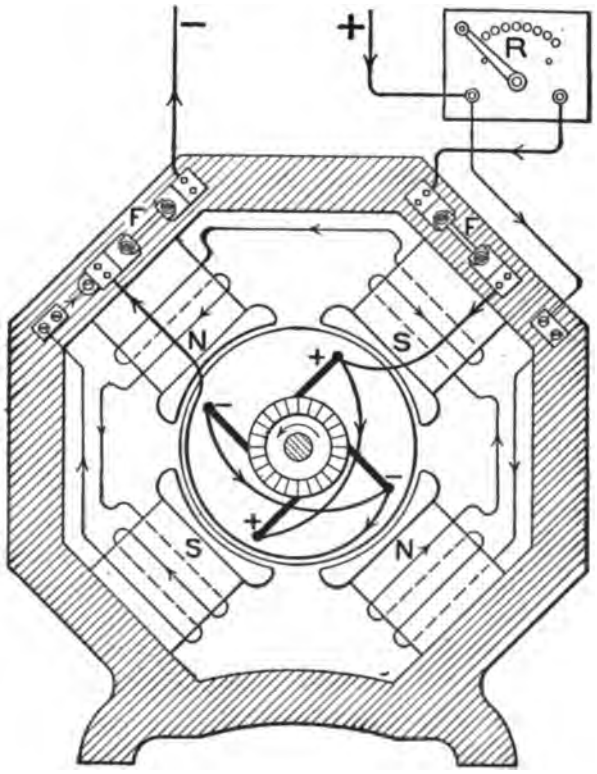


Fig. 21.

2. If the load is removed the speed becomes dangerously high and the motor may tear itself apart.

Uses of Series Motors. The most common use of this motor is in the electric railway where it is usually run on a 500 volt circuit. It is also used in operating hoists, mining machinery, and in general where the load cannot be entirely removed, where the starting torque required is large, and where a constant speed is not necessary.

COMPOUND MOTORS ON CONSTANT POTENTIAL CIRCUITS.

Compound Motors. The compound motor has two independent field windings; a shunt winding gives the main magnetization, and a series winding serves to regulate or to allow starting under heavy load.

Cumulative Compound Motor. This motor has the direction of the current in the series winding the same as that in the shunt winding and hence increases the field strength.

Such a motor has the advantage of a large torque on starting as in the case of a series motor, and an approximately constant speed as with the shunt motor. On starting the series coil is in the circuit, but is cut out when the motor has attained its full speed.

Use of Cumulative Compound Motor. The special use of this motor is where it is frequently stopped and started under a heavy load, and a nearly constant speed is desired.

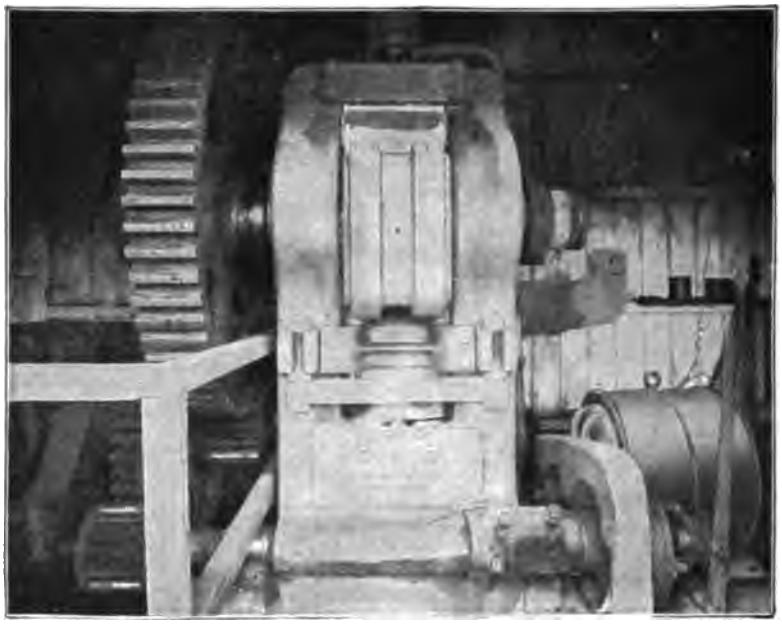
Differential Compound Motor. The series winding in this motor has its current passing in an opposite direction to that in the shunt coil and consequently reduces the magnetization.

This motor gives a more constant speed than the simple shunt motor. We have seen that the speed of the shunt motor decreases *slightly* as the load increases; therefore if the field strength can be weakened with an increased load the speed can be kept up. The current in the series winding is greater the greater the load, hence the magnetization is reduced, and almost perfect speed regulation can be obtained.

It is necessary that the series coil should be inserted *after* starting the motor; otherwise its excessive current would weaken the fields so much that the starting torque would have hardly any value.

The differential motor has the serious disadvantage that with a large overload owing to the excessive current in the series coil, the field magnets may become demagnetized, and instead of the motor keeping up its speed it slows down or stops and is liable to burn out.

Use of Differential Compound Motor. Where a very constant speed is required this motor is used. The shunt motor, however, has a speed which is uniform enough for most purposes, and the differential motor is not much used now.



Western Electric Motor Direct Connected to Rail Cutter in Steel Plant.

Western Electric Motors (encased) Belted to Sand Mill, Showing Severest Conditions to which Motors can be Subjected.

MOTORS ON CONSTANT CURRENT CIRCUITS.

Motors are now in use on constant current circuits to only a small extent. They cannot be made self-regulating, and therefore all have some form of mechanical governor to regulate the speed or torque. Another objection is the usually high potential of the circuits, this being a source of considerable danger.

Owing to the very general introduction of constant potential circuits, and the advantage of constant potential motors over motors which are not self-regulating, the latter have been largely superseded by the former.

Series Motors. The series wound motor is usually the type used on constant current circuits. As a constant current passes through the field and armature windings, the field strength and armature current will have a constant value and consequently the torque will be constant. Hence if the load is reduced the torque exerted remaining the same, the motor will speed up. If the load is entirely removed the speed becomes dangerously high, being much worse than when on a constant potential circuit for in the latter case the armature current is reduced as the speed increases. This increased speed can be prevented if the field is weakened, since the torque is then decreased, the armature current remaining the same.

The motor can be overloaded or held still without its being injured as the current is always the same, therefore no starting resistance is necessary and the throwing of a single switch starts or stops the motor.

Regulation. The usual method of changing the field strength to obtain constant speed is by cutting in or out turns of the field coils. The switch which does this is operated by some form of centrifugal governor, a slight increase of speed causing turns to be cut out and a slight decrease causing them to be inserted.

Another method is by rotation of the brushes. To reduce the field strength the brushes are rotated in a direction such that its magnetization will oppose that of the field magnets. To give a close regulation a comparatively large regulator is required.

MOTOR-GENERATORS.

Motor-generators, or dynamotors commonly called, are nearly synonymous terms applying to a combination of the *direct*

current generator and motor, for the purpose of either increasing or decreasing the voltage of distribution.

The motor which drives the generator, is usually shunt-wound and is connected on constant potential mains.

The simplest case is where the motor is directly connected to the generator, the E. M. F. generated by the dynamo being available for any purpose. Such an arrangement allows a considerable variation of E. M. F. This is usually accomplished by inserting varying resistances in the field circuit of the dynamo; weakening the field, of course decreasing the volts generated.

Where the ratio of transformation of voltage is definite, one field may be common to both motor and dynamo. The armature has independent motor and generator windings which have separate commutators. As the field is common to both the only method of varying the E. M. F. of the dynamo is by inserting resistances in either armature circuit or by shifting the brushes.

CALCULATION OF ELECTRIC MOTORS.

As a direct current dynamo may be used either as a generator or motor, it is evident that the principles of construction and calculation of direct current generators apply equally well to that of motors. Hence for the calculation of an electric motor it is only necessary to determine the corresponding values for a generator at the required speed, and to then proceed as in the calculation of a generator.

The question arises as to what power must the motor be calculated for when considered as a generator. We have seen that the losses in a dynamo are the electrical and the stray power. In a generator the output is equal to the total electrical energy less the *electrical* losses. In a motor the output is equal to the total electrical energy, which is the input, less *all* the losses, that is, the electrical together with the stray power loss. Hence, in making the calculations of a motor we must allow for the stray power loss and figure a generator which at the given speed has an electrical activity in watts equal to

$$\frac{\textit{motor output}}{\textit{gross efficiency}}.$$

Small motors up to 5 horse-power have a gross efficiency of from 80% to 85%, that of motors from 5 to 20 horse-power ranges from 85% to 90%, from 20 to 300 horse-power ranges from 90% to 95%, and motors of more than 300 horse-power have a gross efficiency slightly above 95%.

The E. M. F. for which the generator is to be calculated is the *counter* E. M. F. of the motor, being the E. M. F. generated by the motor at the given speed. This from the motor equation is equal in the case of the shunt motor to

$$e = E - Ir,$$

where e is the counter E. M. F., E the applied E. M. F., I the armature current, and r the armature resistance.

For the series motor

$$e = E - I(r + r_1),$$

where r_1 is the resistance of the field winding.

As the value of the resistances and current are not known, e must be estimated from values obtained by experience. The percentage of the applied E. M. F. which is lost in the armature, or in the case of the series motor in the armature and field winding, varies greatly according to the size of the machine. For shunt motors the per cent of the applied E. M. F. which is lost in the armature, is approximately as follows:

Up to ¼ H. P.	15 %
Up to 1½ H. P.	10 %
Up to 3 H. P.	8 %
Up to 7 H. P.	6 %
Up to 15 H. P.	5 %
Up to 35 H. P.	4 %
Up to 75 H. P.	3½%
Up to 150 H. P.	3 %

For motors of a greater output than 150 H. P. the per cent lost may be a little less. In the case of series motors the volts lost in the armature and field winding may be found by taking about twice the above percentage.

Having determined the electrical activity and the voltage for which the motor is to be calculated, the current capacity is found by dividing the former by the latter.

Example.—It is desired to construct a shunt motor which is to have an output of 5 H. P. at a speed of 1,200 revolutions per

minute, the motor to be run on a 110 volt circuit. Determine the values of the quantities to be used when calculated as a generator.

Solution.—For a 5 H. P. motor the gross efficiency is taken to be 85%. The watts generated by the armature are to be, therefore,

$$\frac{5 \times 746}{.85} = 4{,}400 \text{ watts (approx.)}.$$

Allowing 7% of the applied E. M. F. to be lost in the armature, the voltage to be generated, that is, the counter E. M. F., will be

$$110 \times .93 = 102 \text{ volts (approx.)}.$$

The current capacity will, therefore, be

$$\frac{4{,}400}{102} = 43 \text{ amperes (approx.)}.$$

Hence the armature is to be designed to generate a total E. M. F. of 102 volts, at a speed of 1,200 revolutions per minute, the current capacity to be 43 amperes.

Example.—Suppose we wish to design a series motor for a 220 volt circuit, the output to be 10 H. P. at 900 revolutions per minute. How is the machine to be designed?

Solution. — Supposing the gross efficiency to be 88% the number of watts to be generated is

$$\frac{10 \times 746}{.88} = 8{,}500 \text{ watts (approx.)}.$$

Allowing 12% of the applied E. M. F. to be lost in the armature and field winding the voltage to be generated is

$$220 \times .88 = 193 \text{ volts (approx.)}.$$

The current capacity is to be

$$\frac{8{,}500}{193} = 44 \text{ amperes (approx.)}.$$

Hence the armature is to be designed to generate a total E. M. F. of 193 volts at a speed of 900 revolutions per minute, the current capacity to be 44 amperes.

SECTION 6.

ELECTRICAL MEASUREMENTS.

ABSOLUTE AND PRACTICAL UNITS.

Fundamental Units. All physical quantities such as volume, velocity, force, etc., are derived from, and can be expressed in terms of the three fundamental quantities: **length, mass,** and **time.** Each of these quantities is independent of the other, and can only be measured in terms of its own units.

The system of units in almost universal use by engineers and upon which the electrical units are based, is the **absolute** or **Centimetre-Gramme-Second** system, which is usually abbreviated to the **C. G. S.** system. The fundamental units in this system are: —

The **Centimetre** as a unit of **length;**

The **Gramme** as a unit of **mass;**

The **Second** as a unit of **time.**

The **Foot-Pound-Second** system is also used to some extent, the *foot*, *pound*, and *second* being the units of *length*, *mass*, and *time* respectively.

Derived Units. From the three fundamental units length, L, mass, M, and time, T, are derived all other physical quantities. For example, the area of a rectangular surface is obtained by multiplying the length by the width, or $S = L \times L = L^2$. It is therefore evident that the only unit entering into the measurement of surface is *length*, and that surface is measured by the product of two lengths, or L^2. Similarly, volume is measured by the product of three lengths, or L^3. Velocity which is the rate of motion, or space covered per unit of time, is expressed by $\frac{length}{time}$, or $\frac{L}{T} = L\,T^{-1}$. Hence the only quantities entering into the measurement of velocity are length and time, that is, length and time are the dimensions of velocity. In a similar manner it

SYMBOLS OF PHYSICAL QUANTITIES.

Recommended by the Committee on Notation of the Chamber of Delegates of the International Electrical Congress of 1893.

With the names added in italics of the practical magnetic units provisionally adopted by the American Institute of Electrical Engineers.

Physical Quantities.	Symbols.	Defining Equations.	Dimensions of the Physical Quantities.	Names of the C. G. S. Units.	Practical Units.
Fundamental.					
Length	L, l	.....	L	Centimetre.	Metre.
Mass	M	.....	M	Mass of one gramme.	Mass of a kilogramme.
Time	T, t	.....	T	Second.	Minute; hour.
Geometric.					
Surface	S, s	$S = LL$	L^2	Square centimetre.	Square metre.
Volume	V	$V = LLL$	L^3	Cubic centimetre.	Cubic metre.
Angle	α, β	$\alpha = \frac{\text{arc}}{\text{radius}}$	A number.	Radian.	Degree; minute; second; grade.
Mechanical.					
Velocity	v	$v = \frac{L}{T}$	LT^{-1}	Centimetre per second.	Metre per second.
Angular Velocity	ω	$\omega = \frac{v}{L}$	T^{-1}	Radian per second.	Revolutions (turns) per minute.
Acceleration	a	$a = \frac{v}{T}$	LT^{-2}	Centimetre per second per second.	Metre per second per second.
Force	F, f	$F = Ma$	LMT^{-2}	Dyne.	Gramme; kilogramme.
Work	W	$W = FL$	L^2MT^{-2}	Erg.	Kilogrammetre.
Power	P	$P = \frac{W}{T}$	L^2MT^{-3}	Erg per second.	Kilogrammetre per second.
Pressure	p	$p = \frac{F}{S}$	$L^{-1}MT^{-2}$	Dyne per square centimetre.	Kilogram per square centimetre.
Moment of Inertia	K	$K = MD^2$	L^2M	Gramme-mass-centimetre-squared.	
Magnetic.					
Strength of Pole	m	$F = \frac{m^2}{l^2}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$		
Magnetic Moment	$\mathfrak{M}$	$\mathfrak{M} = ml$	$L^{\frac{5}{2}}M^{\frac{1}{2}}T^{-1}$		
Intensity of Magnetization	$\mathfrak{I}$	$\mathfrak{I} = \frac{\mathfrak{M}}{V}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$		
Field Intensity	$\mathfrak{H}$	$\mathfrak{H} = \frac{F}{m}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Flux of (Magnetic) Force	Φ	$\Phi = \mathfrak{H}S$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$	*Weber.*	*Weber.*
Magnetic Induction	$\mathfrak{B}$	$\mathfrak{B} = \mu\mathfrak{H}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Magnetizing Force†	$\mathfrak{H}$	$\mathfrak{H} = \frac{4\pi NI}{L}$	$L^{-\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	*Gauss.*	*Gauss.*
Magnetomotive Force	$\mathfrak{F}$	$\mathfrak{F} = 4\pi NI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$	*Gilbert.*	*Gilbert*; 1 *Gilbert* = 0.7958 ampère-turns (= 1).
Reluctance (Magnetic Resistance)	$\mathfrak{R}$	$\mathfrak{R} = \nu\frac{L}{S}$	L^{-1}	*Oersted.*	*Oersted.*
(Magnetic) Permeability	μ	$\mu = \frac{\mathfrak{B}}{\mathfrak{H}}$	A number.		
(Magnetic) Susceptibility	κ	$\kappa = \frac{\mathfrak{I}}{\mathfrak{H}}$	A number.		
Reluctivity (Specific Magnetic Resistance)	ν	$\nu = \frac{1}{\mu}$	A number.		
Electromagnetic.					
Resistance	R, r	$R = \frac{E}{I}$	LT^{-1}	.....	Ohm.
Electromotive Force	E, e	$E = RI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Volt.
Difference of Potential	U, u	$U = RI$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Volt.
Intensity of Current	I, i	$I = \frac{E}{R}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	.....	Ampère.
Quantity of Electricity	Q, q	$Q = IT$	$L^{\frac{3}{2}}M^{\frac{1}{2}}$	.....	Coulomb; ampère-hour.
Capacity	C, c	$C = \frac{Q}{E}$	$L^{-1}T^2$	.....	Farad.
Electric Energy	W	$W = EIT$	L^2MT^{-2}	.....	Joule; watt-hour.
Electric Power	P	$P = EI$	L^2MT^{-3}	.....	Watt; kilowatt.
Resistivity (Specific Resistance)	ρ	$\rho = \frac{RS}{L}$	L^2T^{-1}	.....	Ohm-centimetre.
Conductance	G, g	$G = \frac{1}{R}$	$L^{-1}T$	.....	Mho.
Conductivity (Specific Conductance)	γ	$\gamma = \frac{1}{\rho}$	$L^{-2}T$		
Coefficient of Induction (Inductance)	L, l	$L = \frac{\Phi}{I}$	L	.....	Henry.

†N Is the number of windings, and L the length of the solenoid generating the magnetizing force.

may be shown that every physical quantity such as force, work, resistance, etc., may be expressed in terms of one or more of the three fundamental units.

A table of *Symbols of Physical Quantities* is given on page 4. The first column gives the names of the physical quantities, the fundamental, geometrical, mechanical, etc. The second column gives the symbols for each of the physical quantities. In the third column appears what are termed the defining equations, that is, the equations which express the relation between the different quantities. The dimensions of the physical quantities are given in the fourth column. For example, the dimensions of velocity, as we have seen, are $L\,T^{-1}$. The fifth column contains the names of the absolute or *C. G. S.* units, and the sixth those of the practical units.

Definitions of the absolute and practical electrical units are given on the following pages, and are arranged so that they may be easily referred to.

The *C. G. S.* units upon which the electrical units depend are as follows:

Surface. — The unit of surface is the **square centimetre.**

Volume. — The unit of volume is the **cubic centimetre.**

Velocity. — The unit of velocity is the velocity of a body which moves through unit distance in unit time, or one **centimetre per second.**

Acceleration. — The unit of acceleration is that acceleration which imparts unit velocity to a body in unit time, or one **centimetre per second per second.**

Force.—The unit of force is that force which, acting for one second on a mass of one gramme, gives to it a velocity of one centimetre per second. This unit is called one **dyne.**

Work. — The unit of work is the work done in overcoming a force of one dyne through a distance of one centimetre. This unit is called one **erg.**

Energy. — Since the energy of a body is measured by its ability to do work, the unit of energy is also the **erg.**

Power. — The unit of power is the activity when one **unit work** is done in a unit time, or one **erg per second.**

ABSOLUTE ELECTRICAL UNITS.

The **magnetic** units are as follows:

Strength of Pole. — The unit magnetic pole is one of such a strength that when placed at a distance of one centimetre (in air) from a similar pole of equal strength, it is repelled with a force of one dyne.

Magnetic Potential. — Magnetic potential is measured by the work done on unit pole in moving it against the magnetic forces.

Difference of Magnetic Potential. — The unit difference of magnetic potential exists between two points, when it requires the expenditure of one *erg* of work to bring a unit magnetic pole from one point to the other against the magnetic forces.

Field Intensity. — The unit field intensity is that intensity of field which acts on a unit pole with a force of one dyne. This unit is called one **gauss** and is equal to one line of force per square centimetre.

Magnetic Flux. — The unit of magnetic flux is that amount of magnetism which passes through unit area of magnetic field when the field intensity is unity. This unit is one magnetic line and is called one **weber.**

Magnetomotive Force. — This is measured in the same units as difference of magnetic potential. This unit is called one **gilbert.**

Reluctance. — The unit of reluctance is that reluctance when unit magnetomotive force generates in it a flux of one magnetic line. This unit is called one **oersted,** and is the reluctance of a cubic centimetre of air.

From the preceding magnetic units are derived the following absolute **electromagnetic** units:

Intensity of Current. — A current of unit intensity is such that when one centimetre length of its circuit is bent into an arc of one centimetre radius, it exerts a force of one dyne on a unit magnetic pole placed at its center.

Electromotive Force. — The unit difference of electromotive force or potential exists between two points when it requires the expenditure of one *erg* of work to bring a unit of positive electricity from one point to the other against the electric force. A unit

electromotive force is generated by cutting one magnetic line per second.

Resistance. — The unit of resistance is such a resistance that unit difference of potential existing between its terminals, causes a current of unit intensity to flow through it.

Quantity of Electricity.—The unit quantity of electricity is that quantity which is conveyed by unit current in one second.

Capacity. — The unit capacity is such that unit quantity of electricity charges it to unit potential difference.

Inductance. — The unit inductance is such that unit electromotive force is induced by the variation of the current at the rate of one unit current per second.

PRACTICAL ELECTRICAL UNITS.

In practical work the resistance and electromotive forces commonly met with are usually so large that if the absolute electromagnetic *C. G. S.* units were used, the resulting numerical values would be inconvenient. On the other hand, capacities are generally so small that their numerical values in *C. G. S.* units would be very small fractions. For practical use therefore, certain multiples of the *C. G. S.* units of resistance and electromotive force, and a submultiple of that of capacity have been chosen.

The following are the **practical** units:

Resistance. — The **ohm** $= 10^9$ (or 1,000,000,000) absolute units of resistance. The **International Ohm,** which is equal to one true ohm as nearly as known, is the resistance of a uniform column of mercury 106.3 centimetres long and 14.4521 grammes in mass, at the temperature of melting ice. The **megohm** is a resistance of one million ohms.

Current. — The **ampere** $= 10^{-1}$ (or one-tenth) absolute units. This unit is practically represented by the unvarying current which, when passed through a solution of silver nitrate in water, deposits silver at the rate of .001118 gramme per second.

Electromotive Force. — The **volt** $= 10^8$ (or 100,000,000) absolute units, and is that E. M. F. which applied to one ohm will produce in it a current of one ampere. The volt is equal to $\frac{1000}{1434}$ of the E. M. F. of a Clark standard cell at 15° C.

Quantity. — The **coulomb** = 10^{-1} (or one-tenth) absolute units of quantity; being the quantity of electricity conveyed by one ampere in one second. The **ampere-hour** is the quantity of electricity conveyed by one ampere in one hour.

Capacity. — The **farad** = 10^{-9} (or one one-thousand-millionth) absolute unit of capacity; and is the capacity of a condenser which is charged to a potential of one volt by one coulomb of electricity. The **microfarad** is one millionth of a farad, and = 10^{-15} absolute units.

Work. — The **joule** = 10^{7} absolute units of work (or 10,000,000 ergs) and is represented by the energy expended in one second by one ampere passing through a resistance of one ohm. The **watt-hour** is the energy expended in one hour when the activity, or power, is one watt. The watt-hour is equal to 3,600 joules. The **kilowatt-hour** is the energy expended in one hour when the activity is one kilowatt. The kilowatt-hour equals 3,600,000 joules.

Power. — The **watt** = 10^{7} absolute units of power (or 10,000,000 ergs per second), and is the power of a current of one ampere flowing under a pressure of one volt. This unit of power is equal to one *joule per second*, and is approximately $\frac{1}{746}$ of one horse-power, or one horse-power is equal to 746 watts. The kilowatt is equal to one thousand watts.

Inductance. — The **henry** = 10^{9} or (1,000,000,000) absolute units of inductance, and is the inductance in a circuit when the E. M. F. induced is one volt, while the inducing current varies at the rate of one ampere per second.

Values of the Ohm. — The difficulty in determining experimentally the correct value of the ohm and volt has lead to the adoption and use of several different values. Three of these are the British Association (B. A.) ohm and volt, the Legal ohm and volt, and the *International* ohm and volt. The value of the ampere has not changed materially because its absolute value may be easily and accurately determined by means of the tangent galvanometer.

The International Electrical Congress held at Chicago in 1893 recommended the adoption of the *International* ohm and volt. United States, England, Germany, and other countries have now

adopted and legalized the International units, and the ohm and other electrical units have probably now received their definite and final values.

As the B. A. and Legal ohm are still in use to some extent, it is well to know their values in terms of each other.

1 International ohm = 1.0137 B. A. ohms = 1.0028 Legal ohms.

1 B. A. ohm = .9865 International ohm = .9893 Legal ohm.

1 Legal ohm = .9972 International ohm = 1.0108 B. A. ohms.

The **International ohm** represents the true ohm as nearly as the latter is known (see p. 7).

The **B. A. ohm** is the mean resistance of six of the British Association Committee's original ohm coils, now preserved in the Cavendish Laboratory at Cambridge, England, and representing the results of the Committee's experiments of 1865.

The **Legal ohm** is the resistance recommended to be legalized as the standard unit of resistance by the Congress of Electricians held at Paris in 1884. This unit was defined as the resistance of 106 centimetres of mercury, of one millimetre cross section, at 0° C. It has never been legalized in this country but is still employed in technical work to some extent.

ELECTRICAL MEASURING INSTRUMENTS.

Important Principles. When an electric current passes in a conductor, the current causes the same to be surrounded by a magnetic field or by magnetic lines of force. These magnetic lines encircle the conductor and their direction depends upon the direction of the current.

Owing to the presence of these magnetic lines a pivoted magnetic needle will be deflected when placed near the conductor and will tend to set itself at right angles to the same. This phenomenon is illustrated in Fig. 1, the arrows indicating the direction in which the needle will turn. This direction depends not only upon

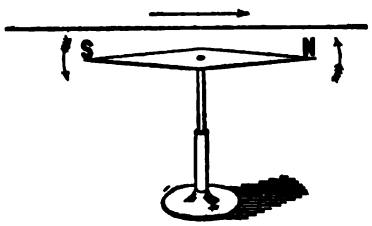


Fig. 1.

the direction of current, but also whether the needle is above or below the wire. If the direction of the current was from right to left in Fig. 1, then the needle would be deflected in an opposite direction to that indicated. If the needle was above the wire and the direction of the current remained as shown, then the needle would be deflected again in an opposite direction.

A convenient rule for remembering the direction of these movements is that suggested by Ampere, which is as follows: Suppose a man swimming in the wire with the current, then if he faces the needle, the north-seeking pole will be deflected towards his left hand.

If the wire passes over the needle and then back under it, as shown in Fig. 2, the effect of the current in both parts of the wire will be to deflect the needle in the same direction. This will be clear by applying Ampere's rule to the upper and lower parts of the wire, the north-seeking pole in each case being deflected as shown. By passing the wire around the needle several times, or in other words by suspending the needle at the center of a coil of wire which carries a current, the deflection of the needle will be much increased, as the effect of each turn is added to that of the others.

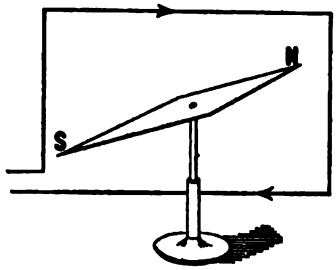


Fig. 2.

This may be more fully understood by considering Fig. 3. When no current is passed through the coil, the needle will come to rest and place itself parallel to the lines of force of the earth's magnetism. The direction of these lines is nearly north and south. Suppose the coil to be placed parallel to the needle and the current then passed through the coil. The needle will come to rest in an oblique direction which will be the direction of the resultant field due to the current in the coil and to the earth's magnetism. The less the strength of the earth's magnetism and the greater the strength of the field due to the current in the coil, the greater will be the deflection of the needle towards a position at right angles to the coil. Hence the deflection may be increased

by increasing the number of turns or length of wire in the coil, and by increasing the current.

Another phenomenon upon which many electrical instruments depend is the deflection of a coil carrying a current. Such a coil, as we have learned, is surrounded by a field similar to that of a magnet, and therefore if it is free to turn, it will take up a position such that the magnetic lines passing through it due to the current, and the magnetic lines of the earth's magnetism will coincide in direction; that is, the coil will move so as to include a maximum number of lines of force. The ends of the coil will then point in a direction which is nearly north and south as is the case with a compass needle. If the coil is in the neighborhood of a powerful magnet the earth's magnetism will then have practically no effect and the position of the coil will be almost entirely influenced by the magnet. The movement of the coil may be caused by a field produced by another fixed coil as well as by a permanent magnet.

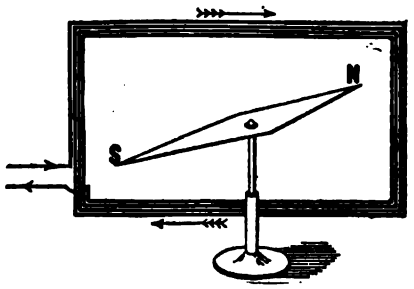


Fig. 3.

Galvanometers. Galvanometers are instruments used for determining the strength or presence of an electric current. These instruments were formerly the only ones used to measure current strengths, and are still largely used in the electrical laboratory for accurately determining the strength of very small currents.

There are two general forms of these instruments; in one the strength of current is determined by the deflection of a magnetic needle suspended at the center of a coil of wire through which the current is passed; in the other the current strength is determined by the deflection of a movable coil carrying the current and which is suspended between the poles of a fixed permanent magnet.

Tangent Galvanometer. This form of galvanometer consists of a coil of wire of many turns and of large radius having a magnetic needle supported or suspended at its center, as indicated in Fig. 4. For accurate results the diameter of the coil must be at least ten times the length of the needle. The needle is usually

about one-half an inch in length and in order that its deflections may be easily determined, it carries a long light pointer which swings over a graduated circle. In using the instrument care must be taken to have the plane of the coil in a vertical position and parallel to the lines of force of the earth's magnetism.

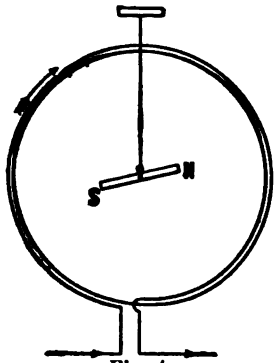


Fig. 4.

Sine Galvanometer. The sine galvanometer is similar in construction to the tangent except that the coil is movable about a vertical axis. Also the length of the needle may be considerably greater thus making the instrument more sensitive. In measuring current strength by the sine galvanometer the coil is first placed parallel to the needle as in the case of the tangent galvanometer, and the needle is then deflected by the passage of the current. The coil itself is next turned about its vertical axis until it is parallel with the deflected needle. Knowing the amount of deflection from the original position the value of the current may be determined.

Astatic Galvanometer. This is a very sensitive form of galvanometer owing to the use of what is known as an astatic pair of needles. If two magnetic needles of equal strength and length are held together with their opposite poles next to each other, as indicated in Fig. 5, they will be independent of the earth's magnetism. One needle will be acted upon to the same degree as the other, and as they are opposite there will be no resultant effect. Hence, if the pair is suspended by a fine silk fibre the needles may come to rest in any position. Owing to the difficulty of magnetizing two needles to exactly the same strength, and of joining them together so that they are parallel, such a pair of needles will have a *slight* tendency to point north and south. If a coil of wire is wound about one of the needles, as shown in Fig. 5, the pair may be deflected by the passage of a very feeble current in the coil. The current passing below one of the needles and above the other,

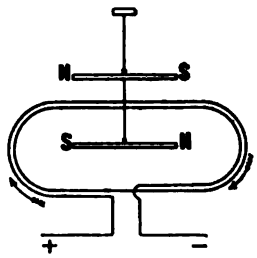


Fig. 5.

tends to deflect both in the same direction; and as the action of the earth upon them is very slight the deflection may be very great. When the deflection is small the current is proportional to the amount of deflection, hence if it is known that a certain current deflects the pair 4°, then a current deflecting the needle 8° will have twice the strength.

Thomson or Mirror Galvanometer. This is the most sensitive form of galvanometer, and is illustrated in Fig. 6. The galvanometer is supported on three screw feet by which the instrument may be leveled. The needles which are usually pieces of steel watch-spring, form an astatic system and may consist of two or more combinations. A small concave mirror is attached to the upper combination and the whole is suspended by a very fine silk or quartz fibre. A permanent magnet called the *control* or *field*

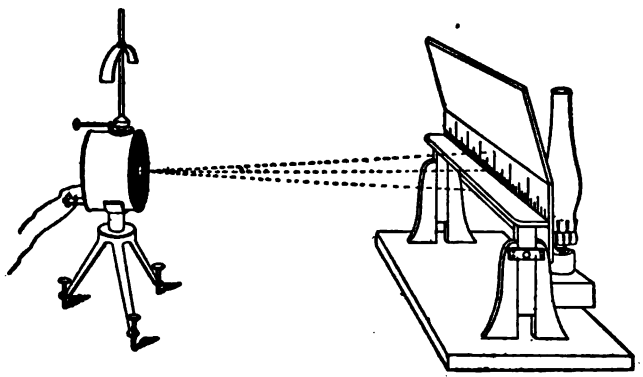


Fig. 6.

magnet is supported above the galvanometer as shown. This may be placed so as to counteract the earth's magnetism, and as it is nearer the upper needle it also serves as a directing or controlling magnet. If the field magnet is removed the magnetic system of needles will come to rest as directed by the earth's magnetism since the system cannot be perfectly astatic. The field magnet may then be lowered in position until the earth's magnetism is counteracted. It is then slightly raised, permitting a feeble directive force to act on the system. Deflection will then take place with an exceedingly small current passing through the coil.

In using this instrument a line of light from a lamp is thrown

on the concave mirror of the galvanometer which reflects it to a graduated scale, as shown in the figure. The scale may be about 8 feet in length and situated about the same distance from the galvanometer. The current is approximately proportional to the deflection of the light on the scale when this deflection is small.

Usually one coil is used, one of the needles being suspended at its center. The coil is divided vertically into two separate parts to give access to the needle and mirror. For greater sensitiveness two coils may be used one above the other, each of which has one needle of the astatic pair suspended at its center. As each coil is divided into two parts, such an instrument is usually called a four-coil galvanometer.

Differential Galvanometer. This galvanometer is used for the purpose of comparing two currents. One coil may be used having two similar independent windings or there may be two separate coils. If equal currents are passed through the windings in opposite directions the resultant effect on the needle at the center will be zero, and there will be no deflection. If the currents are unequal the deflection will be proportional to the difference between them. A Thomson galvanometer may be made differential by connecting the coils so that the current passing through one set will be opposite to that passing through the other.

Ballistic Galvanometer. The needle of this galvanometer is so constructed as to have a slow period of oscillation, and therefore may be used to measure the strength of currents which are of short duration. The charge of a condenser may be measured by discharging it through this form of galvanometer. As the needle is slow to turn the varying impulses of the current of discharge are allowed to produce their full effect. The quantity of electricity flowing through the coil is determined from the maximum deflection of the first swing.

D'Arsonval Galvanometer. The D'Arsonval galvanometer is quite different from preceding forms in that the *coil* is suspended and deflected by the passage of a current. The arrangement is as shown in Fig. 7. The coil through which the current passes is suspended between the poles of a strong, permanent, horse-shoe magnet. The coil consisting of very fine wire is wound upon a small rectangular frame and is suspended by thin platinum silver

strips. The current is passed into and out of the coil through these strips. A small concave mirror is usually carried above the coil as the deflection may then be more accurately determined. Within the coil is fixed a cylindrical soft iron core which serves to concentrate the lines of force passing between the poles, and thereby produces a strong magnetic field in which the coil moves. The tendency of the coil to turn so as to include the greatest number of lines of force when a current is passed through it, is resisted by the torsion of the suspending wires. The deflection produced is directly proportional to the current, the number of turns and the intensity of the magnetic field. The magnet is built up of laminations of hardened steel which is treated so that it will maintain the strength of its magnetism.

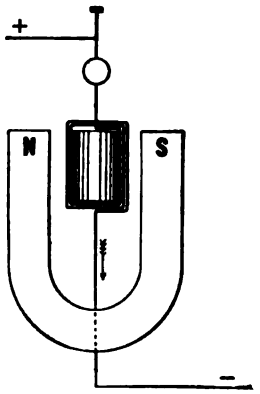


Fig. 7.

The D'Arsonval galvanometer has several important advantages over the Thomson and has largely replaced the latter. Owing to its strong magnetic field this galvanometer is not affected by the magnetism of the earth or other external magnetism. It may therefore be used in close proximity to dynamos or other machines without being affected by them. As the factors upon which the deflection depends may be made invariable for long periods of time, there is no necessity of frequently testing the instrument.

Shunts. If a current is passed through a galvanometer and a very large deflection is produced, there is liable to be a large error in determining the strength of the current, as accurate results are only obtained when the deflection is small. Moreover if a large current is passed through the coil, the instrument will be injured. It is therefore customary to use a shunt about the galvanometer. Part of the current then passes through the galvanometer and part through the shunt, the division of current being inversely as the resistances of the two branches. If the resistances of the shunt and galvanometer are known then the total current may be easily calculated. For example if it was found that .008

ampere flowed through the galvanometer and that the shunt resistance was $\frac{1}{99}$ of that of the instrument, then the total current would be .8 ampere; for the current passing through the shunt was 99 times as great as that through the galvanometer and the total current is the sum of the two, or $100 \times .008 = .8$ ampere. Shunts for galvanometers are adjustable so that the ratio of their resistance to that of the galvanometer is equal to $\frac{1}{999}$, $\frac{1}{99}$, or $\frac{1}{9}$ as desired. With these ratios the total current passing will be respectively equal to 1,000, 100, or 10 times the value of that passing through the galvanometer.

When taking a measurement the shunt should be adjusted so that only a small portion of the current is at first allowed to pass through the galvanometer. If the deflection is too small the resistance of the shunt may be increased until a suitable deflection is obtained. When the shunt circuit is broken the total current passes through the galvanometer obtaining the maximum deflection.

The number by which the current passing in the galvanometer is multiplied to obtain the total current is called the *multiplying power of the shunt.* This is equal to one plus the ratio of the galvanometer resistance to the shunt resistance.

Voltmeters. Voltmeters are instruments used for measuring the potential difference between two points in a circuit. They are provided with a scale graduated in volts over which a pointer is deflected; the position of the pointer indicating the potential difference. In many cases voltmeters depend upon the same principles as galvanometers. If a high resistance is connected in series with the coil of a galvanometer, only a small current will pass when the leads from the coil and resistance are connected to points differing greatly in potential. The current will vary directly as the potential difference and the deflection of the needle will therefore be proportional to this difference.

Weston Voltmeter. This instrument is very much used and is similar to the D'Arsonval galvanometer. The permanent magnet is horizontal instead of vertical, and is similar in shape to the outline of the brass case which encloses the working parts. The magnet is provided with pole pieces which are carefully shaped, allowing the air gap between them and the coil to be small. Fig. 8 illustrates the arrangement. Between the pole pieces *N* and *S*

is fixed a cylindrical piece of soft iron *E* serving to conduct the lines of force. The coil *F*, which is wound upon an aluminum frame, is supported by jewel bearings inserted in fixed brass cups *A* and *B*. A directive force is given to the coil by two delicate springs *C* and *D* which are opposed to each other. The coil carries a light pointer which swings over a scale graduated in volts. A high resistance is enclosed within the case of the instrument and is connected in series with the coils, the current being led to and from the coil through the springs *C* and *D*.

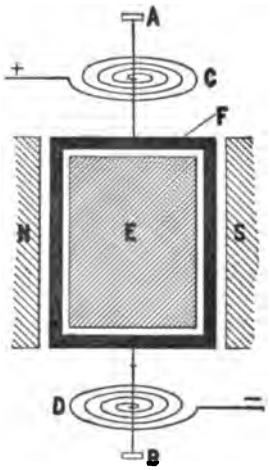


Fig. 8.

A Weston portable voltmeter is illustrated in Fig. 9. The lower right-hand binding post is for the positive terminal. If the negative terminal is connected to the lower left-hand binding post the upper graduation of the scale is used and readings may be

Fig. 9.

taken up to 150 volts. If the negative terminal is connected to the binding post marked 15, then the lower graduation of the

scale is used, the maximum deflection indicating 15 volts. When the latter connection is made the resistance of the instrument is only one tenth of what it is in the former case. The current in the coil (for the same voltage) is therefore ten times as great and the deflection ten times as much. The total resistance of the instrument is about 17,000 ohms. This voltmeter can be used for very high voltages by connecting a large resistance in series. If a resistance ten times that of the voltmeter is connected in series with the instrument, the deflection will only be one tenth of what it would be without this resistance, and hence the maximum deflection will indicate 1,500 volts.

Ammeters. The only essential difference between a voltmeter and an ampere-meter or ammeter, is in the resistance of the instrument. In a voltmeter it was desired that it should have a very high resistance so as to take only a very small current and therefore consume only a small amount of energy. In measuring current strength however. the ammeter must be connected in series in the main circuit, and hence it is desirable that its resistance should be as low as possible so that the energy consumed ($I^2 R$) will be slight. The scale of the ammeter is graduated to indicate amperes directly.

Fig. 10.

The Weston ammeter is very similar in form and construction to the voltmeter, except that in the former instrument the moving coil is connected in parallel with a low resistance shunt through which the main current passes. Therefore the greater the main current, the greater will be the current passing through the coil. The Weston instruments are generally recognized as the most accurate on the market. Besides the form of instrument illustrated in Fig. 9, the Weston voltmeters and ammeters are made in a form for station use. A station ammeter is illustrated in Fig. 10. The connections to the instrument are made

at the back of the switchboard. The instrument illustrated has a translucent scale which is illuminated by an incandescent lamp supported in the rear.

Electromagnetic Ammeters. Many ammeters have been constructed upon the principle of the electromagnet. The Edison pendulum ammeter is a simple example of this class. The arrangement is illustrated in Fig. 11. When the current to be measured is passed through the coil it draws in the soft iron core *C*, which

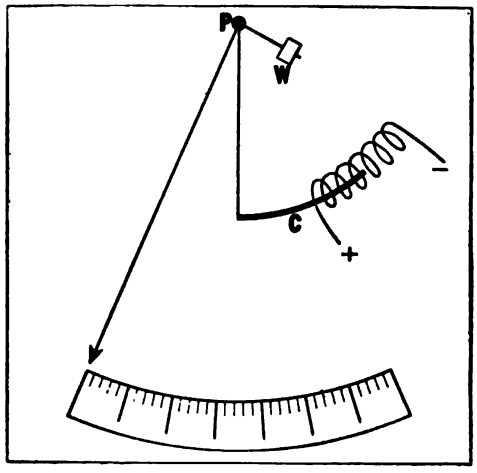


Fig. 11.

is pivoted at *P*. The needle is fixed to the core piece at *P*. The core is drawn into the coil against the force of gravity, the weight *W* serving as an adjustment. The greater the current in the coil, the greater is the deflection of the needle.

Instruments of this type are not very accurate especially at low readings. There is some error due to hysteresis in the iron core, which causes the readings to be too low for an increasing current and too high for a decreasing current. The advantages of this form of ammeter are simplicity and cheapness.

Current Balance. The Kelvin current balance is a very accurate instrument for measuring current strength. It depends for its action upon the force of attraction or repulsion exerted between coils carrying a current. It consists of six coils two of which *A A* in Fig. 12 are movable, and four, *B B B B* are fixed.

The movable coils may be considered as the scale pans of a balance, being supported at the center *C*. The current passes through all of the coils in series, the direction being such that the mutual action causes one of the movable coils to rise and the other to

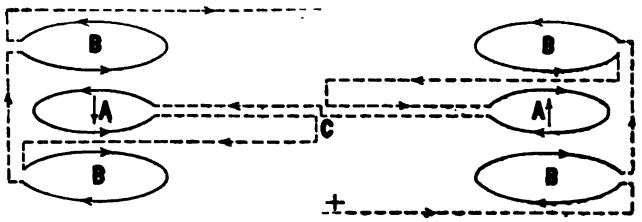


Fig. 12.

descend. This tendency is balanced by a sliding weight on the arm, the position of the slider when the arm is horizontal indicating the strength of current.

Electrodynamometer. This instrument is also used to measure the strength of current by the mutual action of two coils carrying the current. The Siemens dynamometer represented in Fig. 13, is one of the oldest and simplest of these. It consists of two coils *A* and *B* at right angles to each other, through which the current passes in series. One of the coils, *A*, is movable and is supported by a pivot bearing. A spiral spring *C* is attached to this coil and to the torsion head *D*. The current is introduced through mercury cups in which the terminals are immersed. This coil carries a pointer which extends up and over a circular scale. The torsion head also carries another pointer. When a current is passed through the coils, the movable one tends to move so as to include the greatest number of lines of force and to set itself parallel to the fixed coil. The torsion of the spring opposes this movement. The torsion head is then turned until it exactly counterbalances the turning moment of the coil, which is indicated when its pointer is at the zero reading of the scale. The angle

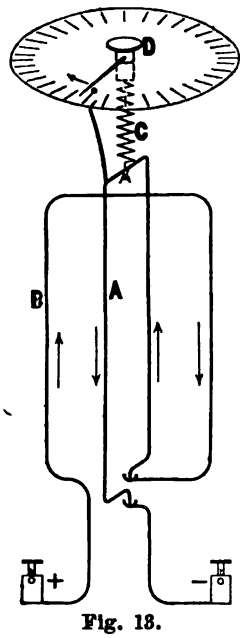


Fig. 13.

through which the torsion head is turned, as indicated by the pointer, varies directly as the square of the current strength. The scale may be graduated to read directly in amperes.

This instrument is serviceable for alternating currents as well as direct, and has the further advantages of being very accurate within certain ranges and of being very free from variable errors.

Cardew Voltmeter. The principle of this instrument depends upon the heating effect of a current. A current passing in a wire heats it and causes it to expand. In the Cardew voltmeter the expansion and contraction of a long fine platinum silver wire is made to move a pointer over a scale graduated in volts. The greater the potential difference at the ends of the wire, the greater will be its current and the more it expands. The voltmeter may be used for either the direct or alternating current as the heating effect is the same. The instrument is subject to many errors and requires therefore the greatest care in its manufacture. It is somewhat awkward to use as it is about three feet in length. Another objection is the comparatively large amount of energy it consumes.

Electrostatic Voltmeters. The principle that two oppositely charged bodies attract each other is applied in the electrostatic voltmeter. The Thomson vertical electrostatic voltmeter is shown in Fig. 14. It consists of two fixed parallel metallic plates *A*, between which is the movable plate *B*. The plate *B* is paddle shaped and supported by two knife edges at its center. This plate carries a pointer which swings over the scale, and is weighted at the lower end to give it a directive force. To measure the difference of potential between two points, the fixed plates are electrically connected to one point and the movable plate to the other. The two fixed plates then become charged with say positive electricity, and the movable plate with negative electricity. The plate *B* is then attracted toward the fixed plates, and deflected from the vertical position to an extent depending upon the difference in potential between them. The force of attraction varies as the square of the difference of potential. The scale is graduated to read directly in volts. It is immaterial whether the fixed plates are charged positively and the movable plate negatively or if the reverse is the case. The force of attraction in each case is the

same. The instrument may therefore be used equally well for alternating or direct currents.

The electrostatic voltmeter is useful only in measuring potential differences greater than 50 volts. They cannot be made delicate enough to measure below that figure with accuracy. They are however, specially desirable in measuring high potential differ-

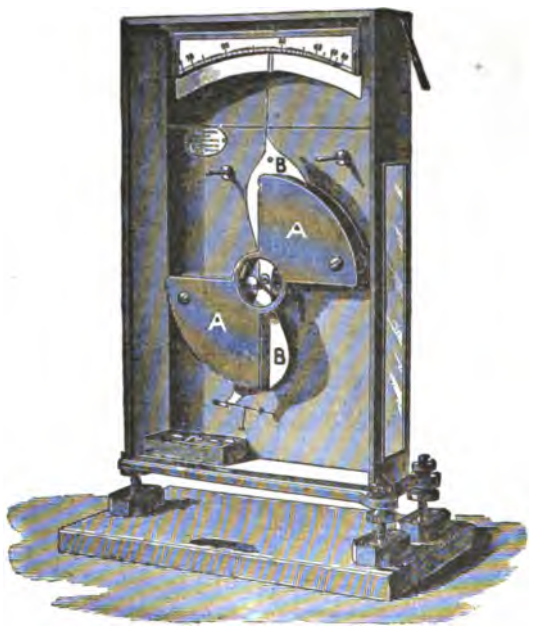


Fig. 14.

ences. They are simple in construction and have the great advantage that they consume no energy, since no current passes through the instrument.

Wattmeters. The power consumed in a circuit supplied with a direct current is equal to the product of the amperes and E. M. F. in volts. An instrument which measures electrical energy must, therefore, take these two factors into consideration.

The Siemens electrodynamometer may be adapted to measure the number of watts consumed in a circuit by having one of the coils serve the purpose of a voltmeter, and the other that of an ammeter. If one of the coils is made of high resistance, having a

large number of turns of fine wire and shunted across the circuit terminals, and the other coil made of low resistance, having a few turns of coarse wire and connected in series with the circuit, then the mutual action between them will be proportional to the product of the volts and amperes. The angle through which the torsion head must be turned to bring the movable coil back at right angles to the fixed coil will be proportional to the energy supplied to the circuit. The scale may be graduated to read directly in watts.

This instrument is more useful in alternating current work than for direct currents. Multiplying the voltmeter and ammeter readings together will give the correct number of watts only in the case of the direct current. With the alternating current this product must be further multiplied by what is known as the *power factor*. The determination of the value of this power factor is somewhat difficult. The wattmeter, on the other hand, gives the true watts directly, and, therefore, is very convenient for alternating currents

Recording Meters. Electrical instruments are sometimes made to give a continuous record of the volts, amperes, or watts of a circuit. This may be accomplished by attaching a pen to the indicating part of the instrument; then if a strip or circular piece of paper is moved by clockwork beneath the pen, a line will be traced showing the volts, amperes, or watts at any time. These instruments cannot be made as sensitive as those which are not recording and are therefore less accurate. They also consume more energy.

The Thomson is one of the best recording wattmeters, and is a motor of simple construction. It consists of two coarse wire coils placed in series with, and a fine wire coil connected in shunt around, the circuit whose power is to be measured. The coarse wire coils form the field which causes the fine wire coil to revolve. The shunt coil is supported in bearings and its rotation is proportional to the energy of the circuit. A copper disk is mounted on the same shaft as the shunt coil and rotates between the poles of a permanent magnet. The currents induced in this disk serve as a drag, the drag being adjusted to give a speed proportional to the watts supplied. The number of revolutions is

recorded by clockwork and the instrument is graduated to indicate watt-hours.

Water Rheostats are very convenient for absorbing power during electrical tests and are easily made adjustable. A very serviceable form is illustrated in Fig. 15. It consists of a stout barrel containing water through which the current is passed. The current is introduced through the insulated wire *A*, which is attached to a terminal plate *D*. From this plate the current passes to plate *C* and through the main *B*. The plates may be of perforated iron; a stove grate serves very well as it gives a large surface contact. To the wire *B* is attached a cord passing over pulleys and having a counter-weight at its other end. The plate *C* may then be raised or lowered and will remain in any desired position. The resistance of the rheostat depends, of course, upon the distance between the plates. Small pieces of wood should be attached to one of the plates to prevent them from accidentally coming into contact, and so producing a short circuit. The conductivity of the water may be greatly increased by the addition of sodium carbonate or sulphuric acid. A rheostat constructed as above is capable of absorbing about 10 H. P.

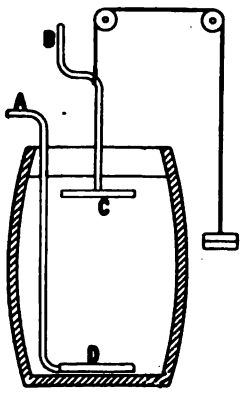


Fig. 15.

Carbon Rheostats. These rheostats consist of a series of carbon blocks or plates in contact with each other through which the current is passed. They are supported by some insulating material such as slate, and arranged so that by turning a hand-wheel the blocks may be pressed closely together or allowed merely to touch. Their resistance is varied in this manner as the closer the plates the less is the resistance. A very exact adjustment may be obtained by the use of these rheostats. Heating caused by the continued passage of a current decreases their resistance.

Wire Rheostats usually consist of German silver wire supported on a frame and arranged so that the whole or parts may be included in a circuit. This is accomplished by making contact at different points along the wire, either by a switch or by sliding clips.

The wires are sometimes strung or wound on wooden frames, and their carrying capacity is then limited by the charring of the wood. A current of two amperes passing through No. 28 German silver wire and a current of eleven amperes through No. 19 wire will cause charring of pine wood.

Wire rheostats which are to carry large currents should not be boxed in, as the free access of air greatly increases the carrying capacity. By immersing wires in an oil bath, their carrying capacity may be increased about four times. Overheating can be prevented by running cold water through pipes immersed in the oil.

Lamp Rheostats. Incandescent lamps are often used as a means of absorbing power or of obtaining a certain E. M. F., or current strength. Such a rheostat may consist of any number of lamps arranged so that they may be connected in series or in parallel between mains. The greater the number connected in parallel the greater is the current taken from constant potential mains.

RESISTANCE MEASUREMENT.

Measurement of resistance is made by comparison with certain standards of known resistance, the different methods of measurement varying to a great degree. The standard resistance coils are made of such alloys as German silver, platinum silver, or platinoid. These alloys have a high specific resistance and change their resistance with rise in temperature to a much less extent than other metals. It is of course desirable that this change should be as small as possible. The size and length of the coils are such that they have resistances of a definite number of ohms at a certain temperature. The coils are insulated with silk or paraffined cotton and are very carefully wound. Each wire is doubled on itself before being coiled up, and then wound as shown at *A* and *B* in Fig. 16. Self-induction and consequent sparking on opening and closing their circuit is thus avoided. The ends of the coils are soldered to brass pieces as *C*, *D*, *E*. Removable conical plugs *F*

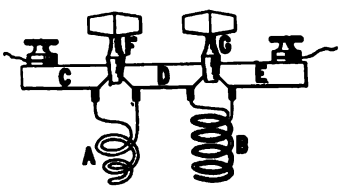


Fig. 16.

and *G* of brass are made to fit accurately between the brass pieces. When these are inserted as shown, the coils will be short circuited and a current will pass directly through *C*, *F*, *D*, *G* and *E* without going through the coils. If *F* is withdrawn the coil *A* will then be inserted in the circuit; if *G* is also withdrawn then coils *A* and *B* will both be inserted, as the current cannot pass from *C* to *E* without going through the coils.

Resistance boxes are constructed consisting of a large number of resistance coils, and of such resistances that by withdrawing plugs varying resistances may be built up. A common form of resistance box has coils of the following ohms resistance: 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1,000, 2,000. A resistance of 497 ohms could be made up by withdrawing plugs corresponding to the coils $200 + 200 + 50 + 20 + 20 + 5 + 2 = 497$, or 768 by coils $500 + 200 + 50 + 10 + 5 + 2 + 1 = 768$.

Resistance by Substitution. By Ohm's law the greater the resistance inserted in a circuit the less becomes the current, provided the E. M. F. remains constant. This gives us a simple although not very accurate method of measuring electrical resistance. If a battery of constant E. M. F., the unknown resistance, and a simple galvanometer are connected in series, the strength of the current passing will be indicated by the latter. Suppose the unknown resistance to be replaced by known resistances, enough resistance coils being inserted so that the deflection of the galvanometer needle is the same as when the unknown resistance was in circuit. The current will then be the same, and as the E. M. F. remains unchanged, the resistances must be equal in each case. The sum of the known resistance coils inserted will then be equal to the unknown resistance.

The advantages of this method are that it is rapid, and that only crude apparatus is required, as the galvanometer and resistance box can be very simple in form. The resistance of the battery and galvanometer should be but a few ohms, otherwise small resistances cannot be measured closely. Only small currents should be used so that the error from heating may be negligible.

Wheatstone Bridge. All ordinary measurements of resistance are usually made by use of the Wheatstone bridge.

The principles of this instrument will be understood from Fig. 17. There are four arms to the bridge with the resistances *M*, *N*, *X*, and *P*. From the points of junction *A* and *C*, wires connect with a battery *E*. A galvanometer *G* is connected between the junction points *B* and *D*. The current from the battery divides at *A* and passes through the resistances *M* and *X*, and *N* and *P*, uniting again at *C*. The fall of potential between *A* and *C* must of course be the same in amount through the resistances *M* and *X*

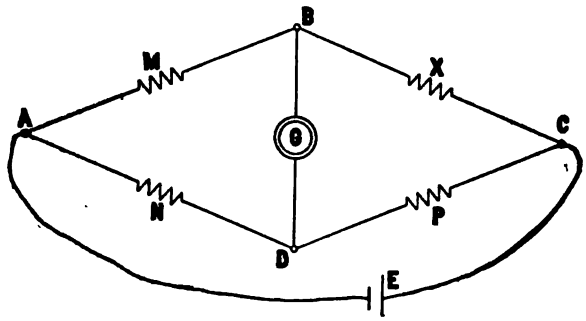


Fig. 17.

as through *N* and *P*. If no current passes through the galvanometer then the points *B* and *D* will be at the same potential, and there will be the same fall of potential in the resistances *M* and *N*, and in the resistances *X* and *P*. Under these circumstances the ratio of the resistances of *M* to *N* will be the same as *X* to *P*, or

$$\frac{M}{N} = \frac{X}{P}.$$

If *M*, *N*, and *P* are known resistances, the resistance of *X* is readily found by the formula,

$$X = \frac{M}{N} \times P.$$

The method of using the bridge will be better understood from Fig. 18. The bridge arm *M* has coils of 1, 10, 100 ohms resistance, and arm *N* coils 10, 100, 1000. The series of coils *P* for obtaining a balance usually has resistances of 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1,000, 2,000 ohms, but coils up to 100 only are shown. There is a key *K* in the galvanometer circuit and a key *H* in the battery circuit. The battery key *H* should always be closed *before* the galvanometer key *K*, and should be

kept closed until after K is opened. This not only insures steadiness in all currents when the galvanometer circuit is closed, but also protects the galvanometer from self-induction currents which would occur if the battery circuit were closed after that of the galvanometer. A reflecting galvanometer is used in making accurate measurements.

In making a measurement of an unknown resistance it is first necessary to gain a knowledge of its approximate resistance. For this purpose the 100-ohm plug is withdrawn from both arms M

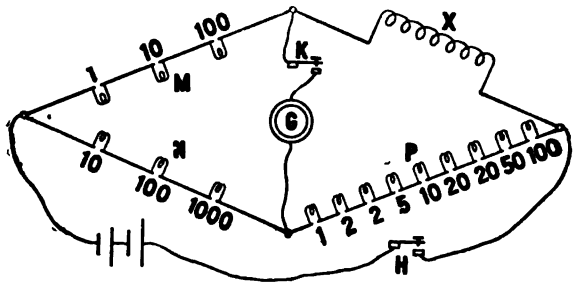


Fig. 18.

and N, the unknown resistance being connected at X. The ratios of M to N will then be unity, and hence for a balance the number of ohms required in the resistance coils P will be the same as the resistance X. The 1,000-ohm plug in P should first be drawn and the keys depressed in their proper order for an instant only. The galvanometer needle or mirror, as seen by the light reflected on the scale, is deflected — say to the right, and the resistance is probably too large. The plug is replaced and the 1-ohm coil withdrawn. On depressing the keys suppose the spot of light is deflected to the left. Then the 1-ohm is too small and the 1,000 ohms too large; also in this case deflections to the right mean that the resistance inserted is too large, and deflections to the left mean that the resistance inserted is too small. The 1-ohm plug is now replaced, and 500, 200, etc., are successively tried until it is found that 12 ohms is too large and 11 ohms too small, that is, the unknown resistance is between 11 and 12 ohms.

Suppose that it is desired to find the correct value of the unknown resistance to the second place of decimals. The ratio of the arms M to N must then be changed so that the resistance coils

P will have a value of between 1,100 and 1,200 ohms when a balance is obtained. The ratio of X to P will then be 11 to 1,100 approximately, or about 1 to 100. To obtain a balance the ratio of the arms M to N must also be 1 to 100. Hence the 100-ohm plugs withdrawn in the first determination are replaced and the 10-ohm plug withdrawn from M and the 1,000-ohm plug from N giving the required ratio. The same ratio could be obtained by withdrawing the 1-ohm plug in M and the 100-ohm plug in N.

The bridge is now arranged for the final measurement. As the resistance in P will now be over 1,100 ohms, the 1,000 and 100-ohm plugs are first removed. Suppose the 50-ohm plug to be also removed, and a deflection to the right shows that this is too great. The plug is replaced and 20 withdrawn, which proves to be too small. The next twenty plug is also withdrawn and a deflection to the left shows the resistance to be still too small. The 5, 2 and 2-ohm plugs are successively withdrawn, the last two ohms proving to be too great. This is replaced and the 1-ohm plug withdrawn, and suppose no deflection is then obtained. The total number of ohms in P is now $1{,}000 + 100 + 20 + 20 + 5 + 2 + 1 = 1{,}148$. The value of X is therefore $\frac{10}{1000} \times 1{,}148 = 11.48$ ohms.

The above example illustrates the general method of using the bridge. Usually the resistance to be measured is known approximately and the required ratio between M and N can be determined without making a preliminary measurement. The possible changes in the ratio between M and N gives the bridge a great range of measurement. When M is 1 and N is 1,000 ohms, measurements of resistance as small as .001 ohm may be made. Bridges are usually arranged with a reversing key so that M and N may be interchanged, hence M could be 1,000 and N 1, and measurements of resistance as high as 4,110,000 ohms could be made with the bridge we have considered.

Portable Testing Set. There are many different varieties of bridges and their form always differs from that of the diagrams in Figs. 17 and 18. A portable testing set including Wheatstone bridge, galvanometer, battery, and keys, is illustrated in Fig. 19. The rheostat of the bridge is made up of coils, 16 in number, of denominations 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1,000,

2,000, 3,000, 4,000 ohms — 11,110 ohms in all. Bridge coils are 1, 10, and 100 on one side and 10, 100, and 1,000 on the other. A reversing key admits of any ratio being obtained in either direction so that the range of the set is from .001 to 11,110,000 ohms.

Fig. 19.

It is, however, impossible to construct a portable galvanometer of sufficient sensitiveness for these measurements, and the actual limits are from .001 ohm to 300,000 or 400,000 ohms.

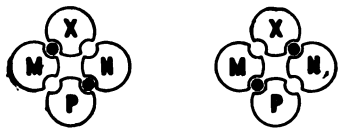


Fig. 20.

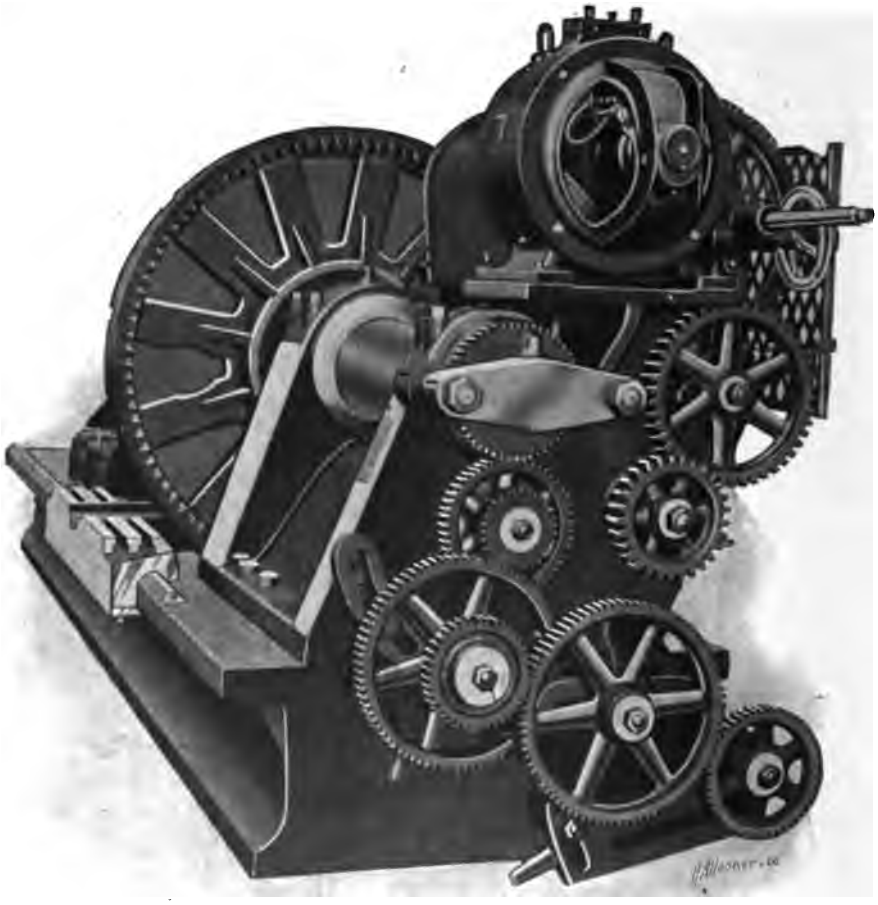
The reversing key, shown in Fig. 20 consists of the blocks M, N, P, and X and two plugs which must both lie on one diagonal or the other. The blocks are connected with the resistances indicated by their letters. In the left-hand figure M is connected with X and N with P, and the bridge arms have the relation

$$\frac{M}{N} = \frac{X}{P}, \text{ or } X = \frac{M}{N} \times P.$$

In the right-hand figure M is connected with P and N with X, the bridge arms then having the relation

$$\frac{M}{N} = \frac{P}{X}, \text{ or } X = \frac{N}{M} \times P.$$

The advantages of having a reversing key in the bridge arms are; the increase in range obtained, six coils being made to do the work of eight, and also that any error in the initial adjustment of the bridge



Western Electric Company's Motor, Geared to a 72-inch Pond Lathe.
The gearing of this Lathe is so arranged that variable speed may be obtained.

arms can be readily detected by having the two arms equal, balancing and reversing. Unless the resistance of the coils inserted in *M* and *N* are exactly equal, the system will be unbalanced after reversing.

The galvanometer, the needle and scale of which are shown at the left in Fig. 19, is of the D'Arsonval type, and the coil is mounted in jewels. As this galvanometer is not affected by external magnetic fields or electric currents, it is suitable for dynamo or shop testing. The key for closing the galvanometer circuit is shown in front at the right.

The battery is made up of six chloride of silver cells contained in the cell box at the right; flexible leads allow the total number in use to be varied at will. The cells will last a number of months even with daily use. The flexible connecting cords have their terminal sockets combined with small binding posts so that connection may be made to an extra battery or other source of E. M. F. if desired. The left-hand key controls the battery circuit.

A plan of the connections of this testing set is shown in Fig. 21. The two lower rows of coils (marked 1 to 4,000) are connected beneath the top at the right by a heavy copper rod and constitute the rheostat arm, or what corresponds to *P*. By withdrawing the proper plugs in these rows any number of ohms from 1 to 11,110 may be obtained. The upper row of coils consists of the two bridge arms, *M* at the left and *N* at the right, with the reversing key between them. The two extremes of the upper row are joined by a heavy copper connection and correspond to the point *A* in Fig. 17. The upper block *X* of the reversing key is connected with the binding post *B*, the block *P* is joined to the left of the middle row of coils while the other end of the rheostat combination is connected with the binding post *C*. The resistance to be measured is connected between the terminals *B* and *C*.

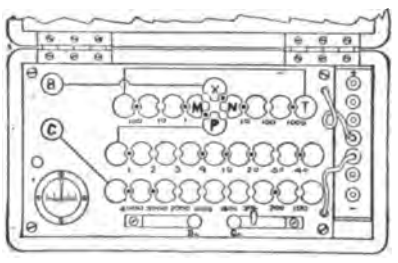


Fig. 21.

Example. — Suppose a balance is obtained with an unknown resistance connected between *B* and *C*, when the plugs are with

drawn as shown in Fig. 21. What is the value of the unknown resistance?

Solution. — The reversing key is arranged so that M is connected with P and N with X, hence

$$\frac{M}{N} = \frac{P}{X}, \text{ or } X = \frac{N}{M} \times P.$$

In the figure $N = 100$, $M = 10$, and $P = 2{,}000 + 1{,}000 + 400 + 300 + 100 + 30 + 3 + 2 = 3{,}835$. Therefore

$$X = \frac{100}{10} \times 3{,}835 = 38{,}350 \text{ ohms.}$$

Ans. 38,350 ohms.

Use and Care of Bridge. Before beginning a measurement it is essential that each plug be examined to see that it is firmly twisted into place, also in replacing a plug the same care should be used. A slight looseness will considerably increase the contact resistance and so introduce errors in the result. For the same reason the plug tapers should be kept clean and the top of the bridge free from dust and moisture. Special care should be taken with the surfaces between adjacent blocks. The plugs should be handled only by their vulcanite tops, and care should be taken not to touch the blocks.

The plug tapers may be cleaned with a cloth moistened with alcohol and then rubbed with powdered chalk or whiting. The powder should be entirely removed with a clean cloth before the plugs are replaced. Sand paper or emery cloth should never be used to clean the plugs or bridge blocks. If there are no idle sockets for the reception of the plugs when they are withdrawn, they should be stood on end or placed on a *clean* surface.

Slide Wire Bridge. The principle of this bridge is illustrated in Fig. 22. The heavy lines represent heavy conducting straps of low resistance. There are binding posts at the ends of each section permitting resistances A, B, R and X to be inserted as shown. Between the ends $C\,D$ is stretched a German silver wire of uniform cross section. A battery and galvanometer are connected as shown. A balance is obtained by sliding the contact point E along the wire until a point is found when no current flows through the galvanometer. Under these conditions the potential at E must be the

same as that at F and as in the Wheatstone bridge the ratio of the arms between the battery and galvanometer connections must be equal, hence

$$\frac{R}{X} = \frac{A+a}{B+b}.$$

The resistances a and b are easily obtained from the lengths of the sections of the wire given by a scale fixed near the wire;

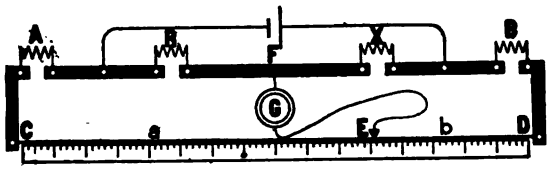


Fig. 22.

then if the resistances of A, B, and R are known that of X may be calculated from the formula

$$X = \frac{B+b}{A+a} \times R.$$

If A and B are replaced by straps of negligible resistance then the value of the unknown resistance may be found from the simple ratio,

$$R : X :: a : b, \text{ giving } X = \frac{b}{a} \times R.$$

Since the resistance of the wire is proportional to its length, the lengths of the sections a and b may be read from the scale and substituted in the latter formula.

This instrument is not well adapted for measuring resistances greater than a few hundred ohms. For very accurate measurements it is necessary to determine and allow for the resistances of the leads from A to C and from B to D.

Example.—If a balance is obtained with the bridge illustrated in Fig. 22, when a is 68.4 centimetres, b 31.6 centimetres, and R 150 ohms, what is the value of X, supposing A and B to be of negligible resistance? Ans. 69.3 ohms approx.

High Resistance Measurement. The standard and most approved method of measuring resistances greater than five or ten megohms is the **direct deflection method.** The main instruments required are a sensitive Thomson galvanometer of high resistance,

a variable shunt resistance for the galvanometer, a known resistance of at least .1 megohm, and a source of constant E. M. F. of 100 volts or more. The connections are shown in Fig. 23. The known resistance R is first connected in series with the galvanometer G and testing battery B, through a key K. Care should be taken that the insulation of the apparatus be very high. The

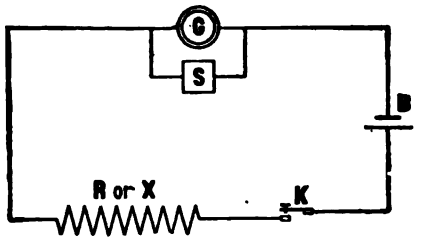


Fig. 23.

shunt S is adjusted to give a suitable deflection of the galvanometer and from this deflection what is known as the *constant* is calculated. The value of this constant is the resistance that must be inserted in the circuit to reduce the deflection to one scale division. The value of the constant is therefore equal to the product of the known resistance R, the scale deflection d, and the multiplying power of the shunt m, or, $\textit{constant} = R\ d\ m$.

As an illustration suppose $R = .1$ megohm, $d = 200$ divisions and $m = 1{,}000$; then $\textit{constant} = .1 \times 200 \times 1{,}000 = 20{,}000$ megohms. This resistance would cause a deflection of only one division, for if $m = 1{,}000$, then if the full current should be passed through the galvanometer, the corresponding deflection would be $1{,}000 \times 200 = 200{,}000$ divisions, as the deflection may be considered proportional to the current. The resistance producing this supposed deflection is .1 megohm, therefore the resistance which would produce a deflection of only 1 division would be 200,000 $\times$ .1, or as found above 20,000 megohms. This follows from Ohm's law, for in order to reduce a deflection by $\frac{1}{200{,}000}$ the current must be reduced by $\frac{1}{200{,}000}$ and consequently the resistance inserted must be 200,000 times as great. This is true, however, only in case the E. M. F. applied remains constant.

After the *constant* has been determined the known resistance R is replaced by the unknown resistance X. The galvanometer

shunt is readjusted if necessary and the deflection obtained is again noted. The value of the unknown resistance is then found by dividing the value of the *constant* by the product of the deflection d_1 and the multiplying power m_1 of the shunt used. To continue our illustration suppose $d_1 = 50$ divisions, and $m_1 = 10$. The deflection, if the full current went through the galvanometer, would be $50 \times 10 = 500$ divisions. A deflection of one division is produced with a resistance of 20,000 megohms, hence a resistance producing a deflection of 500 divisions must be $\frac{1}{500}$ of that; then $X = \frac{20{,}000}{500} = 40$ megohms. These steps may be combined and the resistance given at once by the expression

$$X = \frac{R\,m\,d}{m_1\,d_1}.$$

Example.—In a high resistance measurement by the above method the known resistance was .2 megohms, and gave a deflection of 237 divisions, the multiplying power of the shunt being 100. With the unknown resistance inserted, the deflection was 178 divisions with the full current passing through the galvanometer. What was the value of this resistance?

Solution.—In the preceding formula $R = .2$, $m = 100$, $d = 237$, and $d_1 = 178$; also $m_1 = 1$ as the shunt circuit was open. Therefore,

$$X = \frac{.2 \times 100 \times 237}{1 \times 178} = 26.6 \text{ megohms.}$$

Ans. 26.6 megohms.

Voltmeter Method. Another method of measuring high resistance is that in which a sensitive high resistance voltmeter

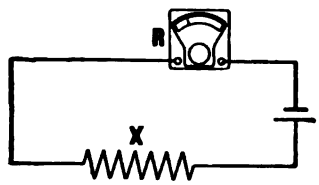


Fig 24.

such as the Weston is used. This method, however, is not so accurate as the preceding and is not adapted to measurements of resistance greater than a few megohms. The voltmeter is con-

nected in series with the unknown resistance and a source of constant E. M. F. as shown in Fig. 24. With such an arrangement the resistance X will be to the resistance of the voltmeter R, as the volts drop in X is to that in the voltmeter. The drop v in the voltmeter is given by its reading and if the applied electromotive force V is known, the drop in X will be $V - v$. We therefore have the proportion,

$$X : R :: V - v : v,$$

and

$$X = \frac{V - v}{v} \times R.$$

The voltage V, which should be at least 100, may be first determined by measurement with the voltmeter.

Example. — A voltmeter having a resistance of 15,000 ohms, was connected in series with an unknown resistance. The E. M. F. applied to the circuit was 110 volts and the voltmeter indicated 6 volts. What was the value of the unknown resistance?

Solution. — Applying the preceding formula

$$V = 110,\ v = 6, \text{ and } R = 15{,}000,$$

therefore

$$X = \frac{110 - 6}{6} \times 15{,}000 = 260{,}000 \text{ ohms, or } .26 \text{ megohms.}$$

Ans. .26 megohms.

Insulation Resistance. The measurement of insulation resistance is performed by either of the two preceding methods of measuring high resistance. The voltmeter method is the simpler, but since it cannot be used to measure resistances greater than a few megohms, the direct deflection method proves to be the more valuable. The insulation of low potential circuits however, need not exceed five megohms, and in testing such circuits the voltmeter method may be used. If little or no deflection is obtained it is then evident that the insulation is at least several megohms, which is all that is desired. As the insulation of high potential circuits must be greater than five or ten megohms the direct deflection method should then be used.

The connections in testing the insulation of a circuit by these two methods are similar to those shown in Figs. 23 and 24, the resistance X being replaced by the insulation of the circuit. This is accomplished by connecting one wire to the line and the other to

ground such as to a gas or water pipe. The insulation of the line from the earth is then included in the testing circuit; the current passing from the battery, or other source, through the voltmeter or galvanometer to line, from line through the insulation to ground, and then to the battery.

The insulation of a dynamo, that is, the resistance between its conductors and its frame, is tested in a similar manner. This resistance should be at least one megohm for a 110 volt machine but two megohms is to be preferred and is customary. This insulation is measured by connecting one wire to the frame and the other to the binding post, brushes or commutator. The insulation is then included in the circuit. Insulation resistance decreases with increase of temperature so that this test of a machine should be made after a full load run of several hours.

The E. M. F. used should be constant and of one to two hundred volts value. Secondary batteries are the best for this purpose, but silver chloride testing cells are much used. The current decreases from its value, at beginning the test, because of the *electrification* or electrostatic charge of the insulation. For this reason the deflection should not be read until after a certain period of *electrification* — usually one minute. This action is quicker in some materials than in others, and is also greater at low than at high temperatures.

Insulation Resistance of Wire. The direct deflection method is used to test the insulation of short lengths of wire. This is sometimes necessary during manufacture or to test the value of different samples.

At least 200 feet of wire is used. This is made into a coil and immersed in a tank of water. A few inches of the ends of the wire are bared and twisted together; a few feet extending outside the tank. One wire of the testing circuit is connected to the ends of the coil and the other to a metal plate also immersed in the water. The plate should be positive, and the current then passes from this through the water and insulation to the core of the wire. The galvanometer must be provided with a short circuiting key, which is always closed when the battery key is operated, allowing no current then to pass through the galvanometer. Cables in water act like condensers when charged or discharged, and the

large current would injure the galvanometer were it not short circuited.

The water should be at a temperature of 75° F., which is generally accepted as the standard. A difference of one degree in the temperature will sometimes cause a difference of several per cent in the insulation resistance. The cable should remain in the water at least 24 hours before the test is made, and it is well to take minute readings of the galvanometer during the first five minutes charging. The insulation resistance is usually calculated from the deflection taken at the end of *five* minutes charging The length of time immersed, temperature, E. M. F., and time of charging should always be stated in a report of a test. Knowing the insulation resistance and length of the sample, the insulation resistance per mile is found by multiplying this resistance by the length expressed in miles. For example, if the insulation for a length of .3 mile was found to be 1,800 megohms, then for a mile of the cable the insulation would be only $1{,}800 \times .3 = 540$ megohms, for of course the longer the cable, the less will be the insulation resistance. The insulation of a good cable should be from 400 to 1,000 megohms per mile.

Example. — In measuring the insulation resistance of 250 feet of wire by the direct deflection method, the deflection after five minutes charging of the cable was 15 scale divisions, the full current passing through the galvanometer. In determining the constant the known resistance was .1 megohm, and the deflection 204 divisions, the multiplying power of the shunt being 10,000. Compute the value of the constant, the insulation resistance of the sample, and the insulation per mile.

Solution. — As the constant is equal to the product of the known resistance, deflection and multiplying power of the shunt, we have,

$$\textit{constant} = .1 \times 204 \times 10{,}000 = 204{,}000 \text{ megohms.}$$

The insulation of the sample is equal to this resistance divided by the product of the deflection after five minutes charging and the multiplying power of the shunt then used. As the full current passed through the galvanometer this latter quantity is unity.

The insulation is therefore

$$\frac{204{,}000}{15} = 13{,}600 \text{ megohms.}$$

The insulation per mile is

$$13{,}600 \times \frac{250}{5280} = 644 \text{ megohms (nearly).}$$

Resistance of Conductors. The conductivity resistance of telegraph lines, cables, etc., which are already installed, is measured by use of the Wheatstone bridge. One end only of the conductor whose resistance is to be measured is then at hand, and this is joined to one of the terminals of the bridge while the other bridge terminal is connected to earth. The distant end of the wire is also connected to earth and the measurement then made in the usual manner.

The earth resistance between the two ends of the wire is then included with the unknown resistance but the former is considered negligible. There are two factors, however, which may lead to considerable error in the result; first, the presence of earth currents, and second, the connections to earth may be defective.

When it is possible the *loop* test should be used. The distant ends of *two* wires are then connected together while the near ends are connected to the bridge terminals. The total resistance of the two wires is then measured. This method does not, however, give the resistance of a single wire. One of the best methods of obtaining this is the following:

Three wires and three measurements are required. Let the resistances of the three wires *1*, *2* and *3* be respectively r_1, r_2, and r_3. First wires *1* and *2* are looped at their distant ends and suppose their resistance is found to be R_1; next wires *1* and *3* are looped and their resistance is found to be R_2; finally r_2 and r_3 are looped and their resistance is found to be R_3. We then have

$$r_1 + r_2 = R_1$$
$$r_1 + r_3 = R_2$$
$$r_2 + r_3 = R_3$$

Adding the equations and dividing by 2, we have

$$r_1 + r_2 + r_3 = \frac{R_1 + R_2 + R_3}{2}$$

Therefore

$$r_1 = \frac{R_1 + R_2 + R_3}{2} - (r_2 + r_3)$$

$$= \frac{R_1 + R_2 + R_3}{2} - R_3$$

Similarly

$$r_2 = \frac{R_1 + R_2 + R_3}{2} - R_2$$

and $$r_3 = \frac{R_1 + R_2 + R_3}{2} - R_1$$

The second terms of the last three formulas contain only known quantities and hence the required resistances may be readily calculated.

The resistance of nearly all field coils of dynamos may be measured by use of the Wheatstone bridge. Shunt field coils of 110 volt machines have a resistance of from about 5 ohms in large machines to 100 or 200 ohms in small machines. High voltage machines have a considerably higher shunt field coil resistance. The series coil of constant current dynamos have a resistance of 1 to 20 ohms. On account of the high self-induction of field coils the galvanometer key should not be depressed until some time after the battery circuit is closed.

The armature resistance of most machines may be measured by the bridge, but it is usually much more convenient to use the "fall of potential" method described below, measuring both current and voltage, and obtaining the resistance by simple division.

Locating Faults. The locating of faults in telegraph lines and cables often involves a number of measurements and considerable calculation. The nature of faults are so varied that one or two methods cannot be applied to all cases.

The kind of a fault which is easiest to locate is where the circuit is completely broken and the fault has no resistance. In this case the conductivity resistance of the wire to the fault may be measured, and dividing this by the conductivity resistance per mile gives the distance in miles to the fault.

The location of faults in dynamos is easily accomplished by the *drop* or *fall of potential method*. A current from an independent source is passed through the armature and connections, the

armature being restrained from moving. The leads from a low reading voltmeter are then applied to different sections of the circuit. The reading of the voltmeter gives of course, the drop in volts in the section included between its terminals. For example, the voltmeter leads may be successively applied to all adjacent segments of the commutator. The potential difference between adjacent segments should be equal; thus a short circuit would be readily located by a decrease in the voltmeter reading. When the current is passed through the field coils, the potential difference at the terminals of each field coil should be nearly equal. A poor contact will be at once indicated by an increase in the reading.

If the current is taken from 110 volt mains, the shunt coils may be connected directly to them, but in testing the armature an additional resistance should be connected in series to prevent a short circuit. This extra resistance should be adjustable so that the current may be regulated. A water rheostat or bank of incandescent lamps serve the purpose very well.

Resistance of Batteries. A very convenient method of measuring the resistance of a cell or battery, is by means of an ammeter and voltmeter. The E. M. F. on open circuit is first measured by the voltmeter. Let this be E. The battery circuit is then closed through an ammeter and suitable resistance; the value of the resistance being such that the output will be equal to the value desired. The readings of the instruments then give the current I, and the E. M. F. on closed circuit e. The drop of potential in the battery is then equal to $E - e$, which is the number of volts necessary to drive this current through the battery. Therefore, by Ohm's law, the resistance of the battery is equal to $\frac{E - e}{I}$.

Another method requires the use of a low reading voltmeter and resistance box. The electromotive force E of the battery is first measured by the voltmeter when the circuit is open. A known resistance R is then connected in series with the cell and the E. M. F. again measured. This voltage will be less than before, as some E. M. F. is lost in the cell itself.

The drop in volts in the cell when the current is flowing is

equal to $E - e$; the drop in the resistance R is equal to e, since this voltage is lost in the external circuit. Then if X is the resistance of the cell we have the proportion,

$$X : R :: E - e : e,$$

as the resistances are proportional to the drop in volts.

Example. — The E. M. F. of a Daniell cell on open circuit as measured by a voltmeter was found to be 1.08 volts. On closed circuit with an external resistance of 15 ohms, the E. M. F. was .90 volts. What was the internal resistance of the cell?

Solution. — Here $E = 1.08$, $e = .90$, and $R = 15$. Substituting in the preceding proportion, we have,

$$X : 15 :: 1.08 - .90 : .90.$$

Therefore, $X = 3$. Ans. 3 ohms.

MEASUREMENT OF ELECTROMOTIVE FORCE.

This is most easily accomplished by connecting the leads from a voltmeter to the points between which the potential difference is to be measured; the voltmeter forming a shunt circuit. Weston portable voltmeters are to be recommended for accuracy and permanency, the average error usually being less than .2 volt.

Potentiometer Method. This method is the standard for the accurate comparison of electromotive forces, and is used for checking standard cells against each other and for calibrating voltmeters.

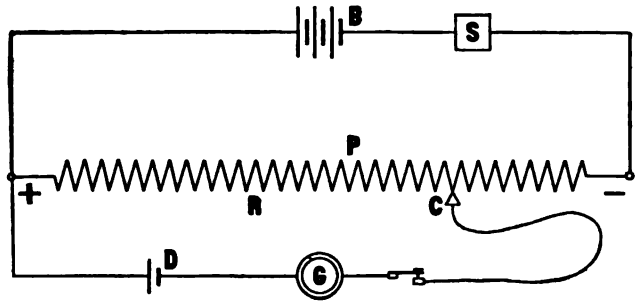


Fig. 25.

The connections are shown in Fig. 25. The potentiometer P consists of a number of coils all connected in series giving a high resistance. A sliding contact piece C is adjustable along P as in the slide wire bridge, and the resistance on either side of C may

be read directly from a scale. A constant battery B having a greater E. M. F. than that to be measured, is connected to the ends of the resistance P, the positive pole of the battery being connected to the left-hand terminal of the potentiometer. The positive pole of the cell D to be tested, is also joined to the left-hand terminal. The negative terminal of the cell is connected through a galvanometer G and a key to the contact piece C. A resistance S is connected in series with the battery B in order to reduce the potential difference across P to any desired amount.

The determination is made as follows:

Before testing the cell D a standard cell of known E. M. F. is first inserted in its place, and C adjusted until there is no deflection of the galvanometer upon closing the key. The cell is connected so that its E. M. F. opposes that of the battery; therefore, when no current flows through the galvanometer, the E. M. F. of the cell must be equal and opposite to the potential difference between the point C and the terminal at the left. The resistance R^1 included between these points is proportional to the potential difference. The standard cell is then replaced by the cell D, and C again adjusted until there is no deflection of the galvanometer. Let the resistance included be R. As the E. M. F. of each cell is proportional to the resistance included, we have,

$$E.\ M.\ F.\ of\ cell : E.\ M.\ F.\ of\ standard\ cell :: R : R^1.$$

The values of R and R^1 are given directly by the potentiometer readings.

Condenser Method. A very convenient method is that in which a condenser is used. A condenser is first charged by a standard cell and then discharged through a ballistic galvanometer. The condenser is then charged by the cell to be tested and again discharged through the galvanometer. The E. M. F. of the cells are proportional to the deflections of the galvanometer.

E. M. F. of Alternating Currents. As the E. M. F. of alternating currents changes from positive to negative and from negative to positive many times a second, it is evident that the above methods which apply to direct currents cannot be adapted to alternating currents. Special forms of voltmeters and dynamometers are therefore necessary.

The electrostatic voltmeter is very largely used in alternat-

ing current work. As the force of attraction between two plates is the same whether one is positive and the other negative, or one negative and the other positive, it is evident that this voltmeter is equally well adapted for alternating or for direct currents.

The dynamometer is also used in alternating current work. For measuring E. M. F. the coils are given a high resistance or a high resistance is placed in series with them. The Weston alternating current voltmeter is of the dynamometer type. In this instrument the movable coil is mounted in bearings, the current being lead to and from the coil by watch springs as in the direct current voltmeter.

Calibration of Voltmeters. The errors in a voltmeter scale which is already graduated, are very accurately determined by use of the potentiometer. The connections, shown in Fig. 26, are similar to those in Fig. 25 required in measuring E. M. F. The

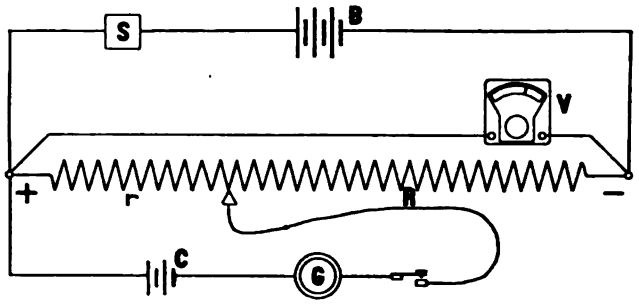


Fig. 26.

voltmeter V to be calibrated is connected across the ends of the potentiometer, which should have a resistance of at least 10,000 ohms. A constant battery B which must have an E. M. F. greater than that of the highest reading of the voltmeter is also connected to the potentiometer terminals. The adjustable resistance S is used to regulate the E. M. F. applied to the terminals of the potentiometer. Standard cells C, in series with a galvanometer are connected as shown, the positive pole of the cells and battery are both connected to the same potentiometer terminal. A resistance should be connected in series with the cells and galvanometer to prevent polarization during trial adjustments, and may be short circuited during the final adjustment.

To calibrate a voltmeter, S is first adjusted until a desired

deflection of the voltmeter is obtained. The contact key or slider is then moved until such a point is found that closing the key causes no deflection of the galvanometer. The E. M. F. of the cells then exactly balances the potential difference between the slider and left-hand terminal. The resistances r and R on either side of the slider are then read from the instrument, and the *true* potential difference across the ends of the potentiometer is calculated as follows: The drop in volts in r is equal to the E. M. F. of the cells C. The drop in volts in $R + r$ is the total E. M. F. available. As the drop in volts is proportional to the resistance, we have

$$\textit{total E. M. F.} : \textit{E. M. F. of } C :: R + r : r,$$

therefore

$$\textit{total E. M. F.} = \frac{R + r}{r} \times \textit{E. M. F. of } C.$$

Example. — In calibrating a voltmeter the shunt S was adjusted to give a voltmeter reading of 27.8 volts. Two standard cells were used each having an E. M. F. of 1.435 volts. The total resistance of the potentiometer was 10,000 ohms, and when a balance was secured the value of r was 1,040 ohms. What correction should be applied to the voltmeter reading?

Solution. — In this case $R + r = 10{,}000$, $r = 1{,}040$ and E. M. F. of $C = 2 \times 1.435 = 2.87$. Substituting in the preceding formula,

$$\textit{total E. M. F.} = \frac{10{,}000}{1{,}040} \times 2.87 = 27.6 \text{ volts (nearly).}$$

The voltmeter reading is therefore too high by .2 volt.

Ans. — .2 volt.

By adjusting the shunt S the errors in various parts of the scale may be determined and a table of corrections made.

If it is desired to graduate the scale so as to give correct readings a slightly different method is employed. In such a case the apparatus is adjusted to give a potential difference of a certain number of volts at the terminals of the potentiometer, and the position taken by the pointer of the voltmeter is marked that number of volts. By succeeding adjustments other points are located along the scale, and this skeleton scale is then subdivided into smaller divisions. Suppose a reading of 10 volts is desired. By

moving the slider, r is given such a resistance that $r : 10{,}000 :: 2.87 : 10$, assuming the total resistance to be 10,000 ohms and that the standard cells have an E. M. F. of 2.87 volts. The value of r is then made equal to 2,870 ohms. The shunt S is then adjusted until there is no deflection of the galvanometer, which gives a potential difference at the voltmeter terminals of 10 volts. Similarly the correct position of the pointer for 20, 30, 40, etc., volts may be determined.

It is desirable to use several standard cells in series at C, as this gives a close average value and also gives larger readings on the potentiometer. When very accurate work is required the standard cells should be placed in a water or oil bath and a correction for temperature made if necessary.

The above method of calibrating voltmeters is that used in the laboratory for calibrating standard instruments. Station voltmeters may then be calibrated by direct comparison with such standards.

The Clark Standard Cell. The *absolute unit* of E. M. F. is that developed by a conductor when it cuts one line of force per second, and the *practical unit* or volt is equal to 10^8 absolute units. In order to have some working standard, the volt is defined in terms of the Clark cell. In this cell the negative element is a rod of pure zinc in a solution of zinc sulphate, and the positive element is mercury in a paste of mercurous sulphate and zinc sulphate solution. This cell is the international standard of E. M. F. and if the standard directions for setting it up are followed, the E. M. F. of 1.434 true volts will be obtained if the temperature is 15° C. The E. M. F. decreases slightly with an increase of temperature, and if the cell is at any other temperature, the correct E. M. F. is given by the formula $E = 1.434 - .0011\ (t - 15\ )$, where t is the temperature in degrees Centigrade.

There are several other forms of cells used as standards, one of the most reliable being the Carhart-Clark cell, which is illustrated in Fig. 27. Above a layer of mercury in the bottom of the cell is the mercurous sulphate and zinc sulphate solution. A piece of cork separates this from a solution of zinc sulphate above it, in which the zinc is immersed. The strength of this solution is determined by the fact that it is saturated at 0° C. Contact is made

with the mercury in the bottom of the cell by a platinum wire passing down through a small glass tube. The E. M. F. of this cell at 15° C. is 1.442 volts, the E. M. F. at other temperatures being given by the formula

$$E = 1.442 \left\{ 1 - .00039\,(t - 15) \right\}$$

In the figure a Centigrade thermometer is shown permanently attached to the cell.

Fig. 27.

In using a standard cell great care should be taken that only very small currents are allowed to pass through it and then only for a short period. To prevent polarization and a consequent decrease of E. M. F. a high resistance should be connected in series, except for final adjustments in zero methods. A short circuit is likely to permanently injure a cell.

MEASUREMENT OF CURRENT.

One of the most accurate and universally applicable methods of measuring current strength is to measure the potential difference across a known resistance through which the current is passing. The value of the current is then given by the formula $I = \frac{E}{R}$. This method is well adapted for the measurement of very large or very small currents.

The simplest method of measuring current strength is by the insertion of an ammeter in the circuit. Ammeters are usually less reliable than voltmeters, but the importance of obtaining current strength accurately is usually less than that of E. M. F.

Alternating currents may be measured by the dynamometer, current balance, measurement of E. M. F. across a known resistance, and by some forms of ammeters.

Ammeter Calibration. A very convenient method of determining the accuracy of ammeters is by measuring the potential difference across a known resistance in the circuit. The connections are shown in Fig. 28. In circuit with the source of E. M. F. is the ammeter A, the known resistance R, and the resistance r

for varying the strength of the current. A standard voltmeter V which has been accurately calibrated is connected across the terminals of the known resistance. Dividing the voltmeter reading by the value of R, determines the current strength and error of the ammeter.

Ammeters can also be very accurately calibrated by direct comparison with Thomson's current balance.

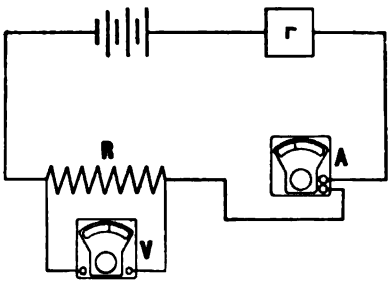


Fig. 28.

MEASUREMENT OF ENERGY.

The wattmeter is used to indicate the power consumed in a circuit. The dynamometer of the Siemens type is one of the most common forms of wattmeter. The high resistance coil is shunted across the part of the circuit in which the energy consumed is to be measured, and the low resistance coil connected in series.

With direct currents the energy consumed in watts is usually obtained from multiplying the reading of a voltmeter shunted across the terminals, by the reading of an ammeter inserted in the circuit.

MEASUREMENT OF QUANTITY.

As the unit of quantity is the ampere second or coulomb, it may be measured by determining the current strength for a certain length of time.

One method of measuring quantity which is largely used depends on the chemical action of a current when passed through an electrolyte, the latter being decomposed by the current. The amount of this decomposition is directly proportional to the strength of the current and to the time. Therefore the quantity of electricity will depend upon the amount of chemical decomposition. The average current may be determined by dividing the quantity by the time. Instruments arranged for measuring quantity or current strength on this principle are termed voltameters.

The Edison *chemical meter* is the voltameter most generally

used. This consists of a cell containing a solution of zinc sulphate, and two zinc plates of a certain size at a fixed distance apart. A low resistance shunt of German silver is connected in the main circuit and the cell is connected about this. If the ratio of the cell resistance to that of the shunt is constant, then a certain fraction of the total current will pass through the cell from which the whole may be determined. This ratio is about 1000. As the resistance of the cell decreases with rise of temperature, a resistance of copper wire is inserted in series with it. The increase in resistance of this with rise of temperature, just equals the decrease in the resistance of the cell. The ratio of the resistances is thus maintained constant. As the current passes from one zinc plate to the other through the electrolyte, the positive plate gradually goes into solution and loses in weight and the negative plate gradually gains in weight. By weighing the plates before and after the passage of the current the quantity of electricity passed may be determined. Usually the weight of the positive plate only is taken, and its lost weight multiplied by a constant to give the number of coulombs or ampere-hours.

The Forbes meter depends upon the heating effect of a current to record the number of ampere-hours. The current is passed through a number of fine wires connected in parallel. The heating of these causes a rising current of warm air and this rotates a spindle carrying light mica vanes. The number of ampere-hours is determined from the number of revolutions of the spindle.

If the potential of the circuit is constant the number of watt-hours is found from the ampere-hours if the latter is multiplied by the voltage of the circuit.

MEASUREMENT OF CAPACITY.

Capacity and its measurement becomes of considerable importance in the case of submarine and underground cables. Such cables actually become condensers, the internal wire forms the inner coating, the water the outer coating and the insulation forms the dielectric between them. This presence of capacity in cables makes it necessary to charge them before a signal is indicated at the distant

end, and thus causes retardation in the transmission of signals and also enfeebles the strength of the current at the distant station.

Ordinary condensers may be charged or discharged almost instantaneously. The charging and discharging of cables however, requires so much time that the accurate measurement of their capacity is very difficult. In discharging, a cable yields most of its charge at first, and then gradually gives up the remainder.

Direct Deflection Method. In this method of measuring capacity, which is the simplest and most generally employed, a standard condenser is first charged by a battery and then discharged through a ballistic galvanometer. The condenser of unknown capacity is then similarly charged and discharged. The capacities of the two condensers are proportional to the galvanometer deflections.

Example. — A condenser of .3 microfarad capacity was charged by a battery and when discharged through a galvanometer gave a deflection of 103 scale divisions. A condenser of unknown capacity was then charged by the same battery and on discharge gave a deflection of 128 divisions. What was the unknown capacity?

Solution. — As the capacities are proportional to the deflections we have the proportion,

$$x : .3 :: 128 : 103$$

$$\text{or } x = \tfrac{128}{103} \times .3 = .37 +$$

Ans. .37 + microfarad.

Divided Charge Method. This method gives more accurate results than the preceding and is often used in measuring the capacity of long cables. The connections are shown in Fig. 29. The key k is first depressed, charging a condenser C of known capacity. The key k is then opened and the key K raised, discharging the condenser through the galvanometer G, giving a deflection D. C is then again charged, k opened and K depressed. This connects

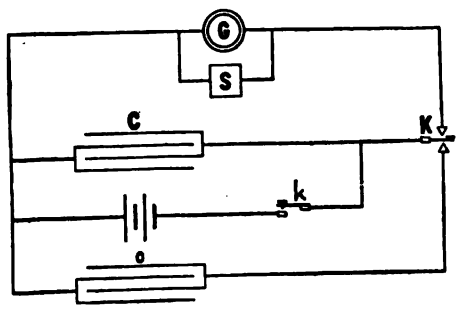


Fig. 29.

the standard condenser with the condenser c of unknown capacity, and shares part of its charge with the same. The division of charge is proportional to the capacities. By raising K the condenser C is again discharged through the galvanometer, giving a deflection d. As the deflections are proportional to the charge of C in each case, the capacity of C is to that of c as the first deflection D is to the decrease in deflection which represents the charge of c, that is,

$$C : c :: D : D - d,$$

therefore,

$$c = \frac{D - d}{D} \times C.$$

Bridge Method. In this method the capacities of a standard and of any other condenser are balanced in the arms of a bridge. Fig. 30 illustrates the necessary connections. The standard C and that of unknown capacity c, form two arms of the bridge, and the adjustable resistances R and r complete it. When the key K is raised, current flows from the battery and charges the

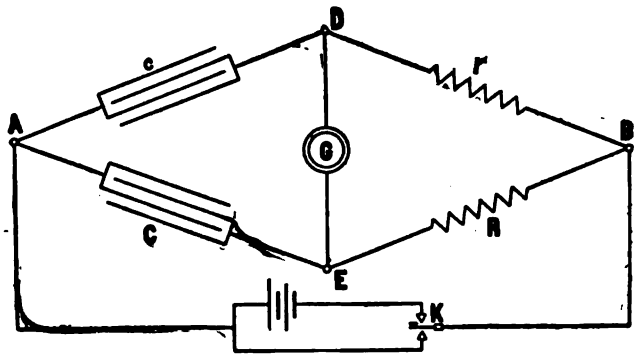


Fig. 30.

condensers; on depressing the key the condensers are discharged. The resistances r and R are adjusted until during charging and discharging there is no deflection of the galvanometer. The potential at D and E will then be the same, and the condensers are therefore charged under the same potential; the quantity of electricity required to charge them will then be proportional to their capacities. When there is no deflection of the galvanometer in charging or discharging, the drop in the resistances r and R must be the same. Suppose the capacity of c to be larger than that of C: then

in charging, the current passing through r must be greater than that through R. As the drop is proportional to the product of current and resistance; then in order to have the same drop in r as in R if a larger current flows through r its resistance must be less. The capacities of the condensers are therefore inversely as these resistances, or

$$c : C : : R : r.$$

Example. — With condensers connected as shown in Fig. 30, it was found that there was no deflection of the galvanometer when r was 2,700 ohms and R 7,300 ohms. The capacity of the standard condenser C was .2 microfarad. What was the capacity of c?

Solution. — Substituting in the preceding proportion, we have,

$$c : .2 : : 7{,}300 : 2{,}700,$$

therefore $c = .54$. Ans. .54 microfarad.

Thomson's Method. If two condensers are charged with

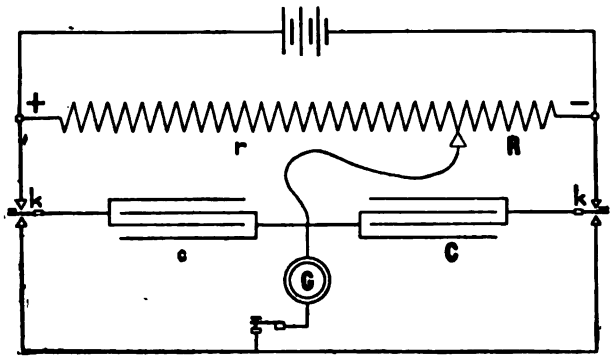


Fig. 31.

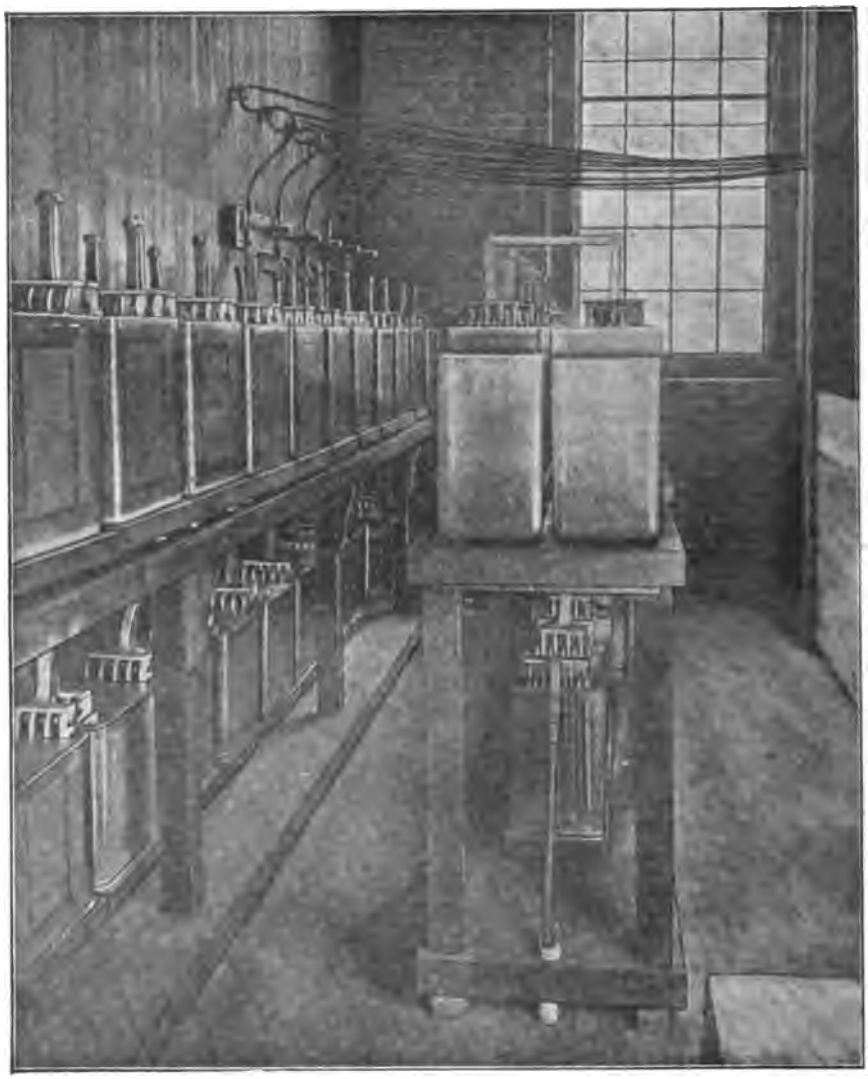
equal quantities of electricity and then discharged by connecting them in series + to — and — to +, the two charges will exactly neutralize each other and no resultant charge will remain. To charge two condensers of unequal capacity with equal quantities of electricity requires a higher E. M. F. at the terminals of the smaller condenser, that is, the E. M. F. applied at the terminals must be inversely as the capacities. If the ratio of the E. M. F.'s is determined, then the ratio of the capacities of the condensers is also obtained. These principles are involved in Thomson's method.

The connections are shown in Fig. 31. If the two keys k are raised the condensers c and C will be charged by the battery. On depressing these keys the condensers are connected in series and their charges mixed. If the charges were equal they would neutralize each other, if unequal a residual charge would remain, which would be divided between the two condensers. Upon closing the galvanometer key any residual charge would then pass through the galvanometer producing a deflection. The potential at which the condensers are charged is regulated by a slide coil bridge or potentiometer. The slider is manipulated until the voltages of charging are in an inverse ratio of the capacities. When this is the case, after mixing there is no resultant charge and the galvanometer will show no deflection. In making the measurement, the condensers are repeatedly charged and discharged and the slider adjusted until a balance is obtained.

As there is a gradual fall of potential along the potentiometer from the positive to the negative terminal the position of the slider determines the voltage at which the condensers are charged. For example the difference of potential between the positive terminal and the slider is the voltage at which condenser c is charged, and that between the slider and the negative terminal is the voltage at which condenser C is charged. Changing the position of the slider of course varies the ratio of these two voltages. These voltages will be directly proportional to the resistances r and R. Hence when the charges exactly annul one another the resistances r and R will also be inversely proportional to the capacities of the condensers, or

$$c : C :: R : r.$$

Knowing the value of the resistances R and r and the capacity of a standard condenser C, the capacity of c may be calculated. The charging and mixing should last a certain length of time, say ten seconds for each process. In measuring the capacity of long cables the time of charging is sometimes as long as five minutes.



Typical Installation of Chloride Accumulators.
(By courtesy of the Electric Storage Battery Company.)

SECTION 7.

THE ELECTRIC TELEGRAPH.

Apparatus and the Morse Code.

In order to get the beginner's point of view, it is taken for granted that the reader knows nothing of electricity or the practice of telegraphy. If there is a slight knowledge of either of these, so much the better; but as a starting-point, we will consider that altogether familiar use of the electric current in the ringing of a door-bell by pressing on a button. In so doing the new arrival "telegraphs" the fact to the household, and asks for admission, and those within respond to his message, although neither the one nor the other may know a dot from a dash. The simple combination of battery, wire and apparatus by which this action is carried on is as truly a telegraph circuit as is the longest in the land, and a glance at its elements will serve as a stepping stone to the more complex apparatus of the electric telegraph.

The different parts of the electric-bell device may be seen in their relation one to the other by reference to Fig. 1. In the center is the push-button P, pressing upon which brings the point of spring S into contact with the metal strip R. On one side is the cell A, with its two poles C and Z; on the other is the bell, with its electromagnet M, its armature hinged upon a spring K, carrying a hammer H, to strike the bell. Attached to the back of the armature is a spring, making contact at D with a back-stop T. These parts are so adjusted that when the armature is attracted by the magnet the contact at D is broken. Looking now at the diagram, if the wiring is traced from the point C back to the point Z, but one break will be found in the continuous contact of the wire with the different parts, and that is between the spring S and the strip R.

If, by means of the push-button, S is forced against R, the break is closed; the current speeds from the point C of the cell

through the wire back to the point Z, charging the electromagnet M, which attracts armature-carrying hammer H. But by this movement the contact, and therefore the electric circuit, is broken at D, the current ceases, electromagnet M releases the hammer H; contact of the armature and back-stop at D is thus restored; magnet M is again charged, attracting the armature; the result being a vibration of the hammer, continued as long as spring S is kept in contact with R. The energy is derived from the cell, but the control of it lies in the push-button; and the effect of the making and breaking of the circuit at R is such as to appeal to the ear. By means not very different the same organ is addressed in teleg-

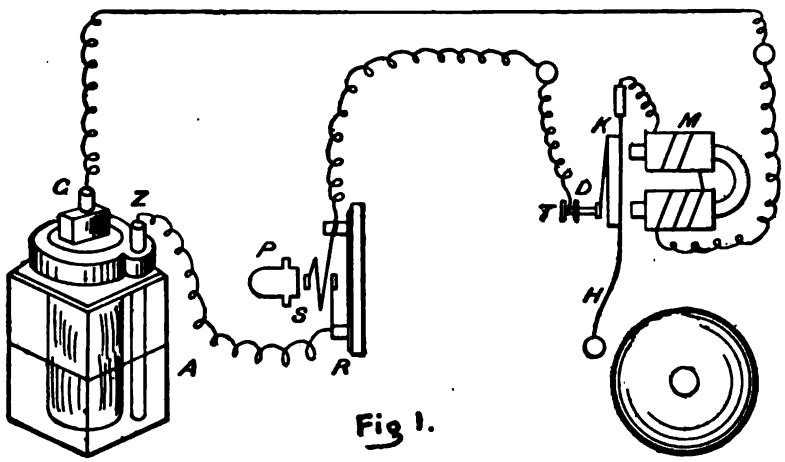


Fig 1.

raphy; but the appeal is of a kind legible only to the expert. The bell device serves the further purpose of bringing the learner face to face, at the outset, with the fact of the inconceivable speed of the energy he is employing,— a feature which allies it to light in the velocity of its movement.

Having now gained a general idea of the action of a current in moving an armature, we will suppose that the reader, if in a city, has stepped into one of the many branch offices of a great telegraph company, or it may be into a town or village office of the same, and for the first time is taking notice of the outfit. In such an office there will be seen (secured to the wall) a small switchboard, but the interest centers on the table or desk, where there are usually three forms of apparatus, known as the relay,

key and sounder, with the wires connecting the various parts. On the window-sill, or under the table, is the battery of one or two cells, for the operation of the sounder, whose clicking at once arrests the attention of the visitor. The uninitiated, listening to these sounds for the first time, naively express surprise that they "can make nothing of them." This set of apparatus, installed in thousands of small offices all over the continent, and duplicated many times in the large offices, is shown in outline in Fig. 2. The relay, the most important instrument in the set, is not heard at all; the main battery which operates it may be scores of miles away; the current from it has its path in the main, or air, line

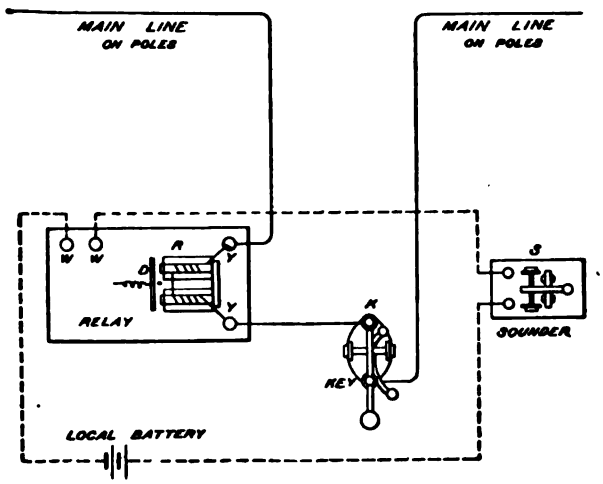


Fig 2.

coming in from the pole in the street. Passing through the coils of the relays and the keys, it makes its exit through the office window, to resume its place on the poles which support it to the terminus of the line.

Examining Fig. 2 and comparing it with the bell-ringing device shown in Fig. 1, we find the cells of battery and the wiring common to both; the sounder corresponds to the bell proper; the key marked K answers to the push-button. The dotted lines in Fig. 2 represent the "local" circuit, and the cells are the "local" battery, so called because its action is confined to the

place (Latin, *locus*) or station with which it is immediately connected. It presents in miniature all the essential features of the main-line circuit; and if the *wherefore* of this pair of conductors and their connected parts is understood, the method of Morse telegraphy is within easy distance; and with the little light gained from the comparison of the electric bell with the telegraph circuits, we may take a step further in advance. For closer examination, therefore, this local circuit and its parts are reproduced on a larger scale in Fig. 3 and with more lettering. Each of the two cells of battery is surmounted by two projections called poles,—the terminal connections of two dissimilar substances, as copper and zinc, or zinc and carbon. What goes on in the cell

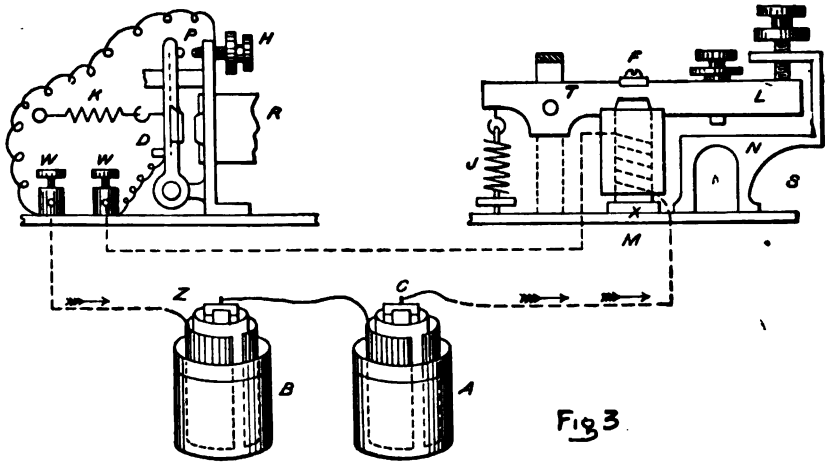


Fig 3

itself need not detain us here; all that need be noted now is that by outwardly joining up the cells so that the unlike substances are in metallic contact, a current is the result. First the carbon terminal or pole of one cell is connected to the zinc pole of the other; then from the carbon pole C of cell A runs a wire (dotted line) which can be traced through the coil of magnet M; thence to the armature D, and local points at P of the relay R back to the zinc pole Z of cell B. Of relay R only the moving parts are shown. The thumbscrews, wherever found, have connected to them wires from the different parts of the instrument, and are merely conveniences for making contact with the outside wiring.

Besides the battery of two cells and the conducting wires (dotted lines), the circuit, as already intimated, includes an electromagnet, consisting of a pair of upright coils (only one is shown), which, with the surmounting armature F and its adjacent parts, constitutes the sounder S. Each of the two upright coils of wire has a core of soft iron with a strip of iron X, joining them underneath. Close to the upper ends of the cores, but not touching, is a strip of soft iron F, called the armature, secured to a lever L, moving on trunnions T, at one end, its free end moving between two stops, the spring J serving for its adjustment. The movement of armature D of relay R is also limited by stops, and, tracing our dotted line circuit, we find a point P, where the circuit may be "broken" by withdrawing armature D from the front-stop H; just as in the case of the push-button, the circuit is "made" by pressure on the button, and "broken" by the withdrawal of it. In other words, in this armature D, with its front and back stop, and spring K, we have a telegraph key in a form the simplest and most easily understood, but not the most easily operated.

In a local circuit arranged as in Fig. 3, when armature D of relay R rests against its front-stop H, the current magnetizes the cores of electromagnet M of the sounder; armature F is strongly attracted thereto, making a sharp click as it strikes the down-stop N; a reverse or upward movement is determined by spring J if armature D of the relay is withdrawn from the front-stop, giving a sound less sharp than in the downward movement. The difference in sound between the front and back-stroke of the lever is something of which the learner must early take note, because the front is the marking stroke, or the one from which he reads, the back-stroke being unintelligible. In the former case (armature D against the front-stop), the circuit is said to be "made" or "closed;" in the latter it is "broken" or "open." Closed and open are the terms in general use among telegraphers. In the case of the electric bell, the push-button puts us in control of the energy which attracts the hammer to the gong. In the local arrangement we have been considering, the control of the sounder S lies in the armature D, whether moved by the finger, or in the usual way by the current.

In this dotted-line arrangement the wires are the carriers or

conductors of an energy which has its source in chemical action in the cells. In the poverty of language it is said to "flow" or "run" within the cell from the zinc to the copper plate, or from zinc to carbon; and in the external portion (dotted line) from copper or carbon to zinc. Moving thus along the conducting wire and through the connected instruments it is called a current (Latin, *curro*, to run) and in doing so it is said to make a "circuit," which may vary in length from a few feet to hundreds of miles. Its velocity is such that wherever a fitting pathway is afforded, it seems not so much to flow as to be omnipresent. In a series of tests made in New York by the United States Coast Survey, two separate wires were obtained to San Francisco, where they were joined, or, as telegraphers say, "looped." To each of the New York ends of the wire, instruments were connected, and signals sent on the one wire returned on the other in a space of time just perceptible. The current had traversed the continent and back in a small fraction of a second,— a kind of movement which the words "flow" and "run" hardly describe.

It is the purpose of this description, to explain to the reader how it is that the signals heard on the sounder can have a meaning to the operator; how it is that the down and up movement of the lever of the key K, Fig. 3, can transmit intelligence to a distant station; then, briefly at first, but later on more completely, to instruct him in the method of operation, use and adjustment of each instrument in the set, so that in a reasonable period of time he will himself be able to send and receive the signals which before were unintelligible. At this point a number of questions may suggest themselves to the thoughtful student. Some of them, it may be, cannot be answered; others may belong to the theory of the art; but our present aim is entirely practical, the point being to beget in the student the ability to translate writing and speech into the "Morse" language; the consideration even of the main-line circuit is therefore deferred.

Summing up the examination of the local circuit there are

(1) The cells of battery as the source of energy,

(2) The conducting wires,

(3) The sounder S, consisting of an upright electromagnet having for an armature a movable lever; and

(4) A point P in the circuit at which, by a movement of the armature D of relay R, we can control at will the armature of sounder S.

In speaking of the relay R, Fig. 3, and its armature, the remark was made that in it we have a telegraph key in form the simplest and most easily understood, but not the most easily operated. Remove the dotted line wires from the thumbscrews of relay R and insert them, as in Fig. 4, in the terminals of a key K'. By this change we have made of the local circuit a "learner's outfit"— battery, key, sounder and connecting wires. Even with

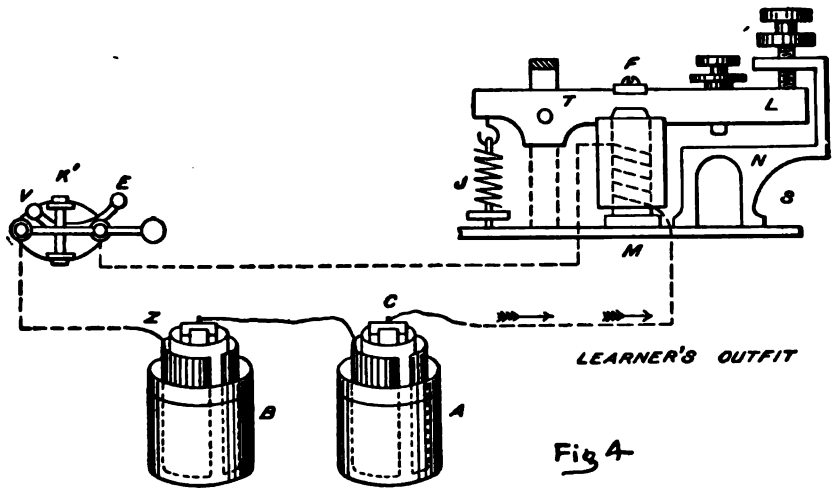


Fig 4

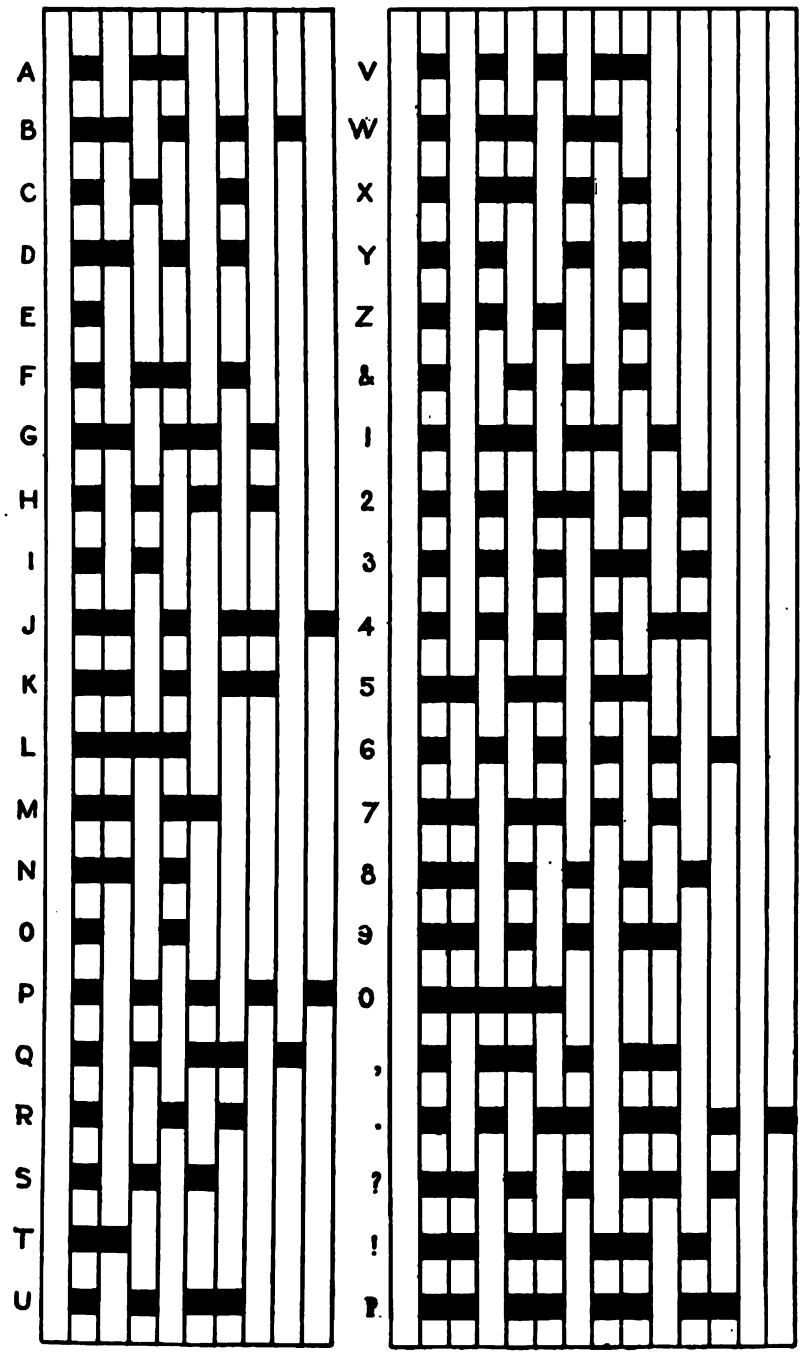
these, signalling to considerable distances can be carried on, and the medium for it is the Morse Telegraph Code, whose elements and their combinations to form letters are now to be taken up.

THE MORSE CODE.

It is taken for granted now that the student is provided with "a learner's outfit," comprising the apparatus shown in Fig. 4. The key K is provided with a curved arm E, hinged at V. By moving this to the right the key is opened. If, by tapping on the rubber knob of the lever, dots are made on the open key, it will be found that the armature of the sounder follows its movements. Having attained thus the control of an electromagnet, only a time element is needed in connection with the movements of the key to

produce intelligible signals. In other words, if the open key is closed, by depressing the lever, now for a short, now for a longer time, or if the time between the moments of depression is varied, it is possible, by assigning the letters of the alphabet to different combinations of these movements, to make the instrument spell out the words of a language. To this end there was devised a system of dots, spaces and dashes, so arranged and combined that, singly or in groups, they are made to represent the different letters, figures and characters of the English language. If the learner (the key being open) hits the rubber knob a short, sharp blow with the finger, the sounder will give two clicks, one with the downward motion of the armature and one with the upward. The former has a sharp click, the latter a dull sound called the "back-stroke." The signal thus formed is called a dot, and its prolongation by a longer depression of the key is a dash; the down-stroke of the armature marks the beginning of a dot or dash, and the up or back stroke its end. In the movements for the production of the signals the time unit is the dot; by its duration all the dashes and spaces are measured. The single dot, produced as described, is the signal for the letter E, the letter in most frequent use having assigned to it an element the simplest and most easily formed. Prolong the dot to twice the time and we have the dash — the signal for the letter T; to four times the time, a longer dash, forming the letter L; to five times the time, and we have the signal for a cipher (0). To the hand the only difference between a dot and a dash is a longer depression of the key; to the ear the difference is in the interval between the down and up, or back-stroke of the armature. If the back-stroke were absent it would be impossible to distinguish E, T and L one from the other. It is not an uncommon thing for even the experienced operator to "get the back-stroke," in which case he dampens the up-stroke of the sounder with his finger until the ear catches the down-stroke again.

In the selection of the combinations which make up the code of signals, the principle, "the easy signal for the frequent letter," is observed throughout. The time value of the dot is constant, but the dash and space have each three different lengths. Two dots separated by a space of time approximately equal to a dot


A
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!

represent the letter I, but two dots separated by a space equal in time to two dots represent O. The former is a mere interval, the latter is called the letter space; the word and sentence space are multiples of it — usually twice for the former and thrice for the latter. In naming the elements of the signal for the letter O, for example, they are read "dot, space and dot."

The entire scheme of the Morse Code, with its dots, spaces and dashes, their combinations and their relative time values computed according to the unit of time — the dot — and the letters, figures and characters they represent, is shown graphically in the accompanying chart, which the student must now, for a time at least, make his constant guide and reference.

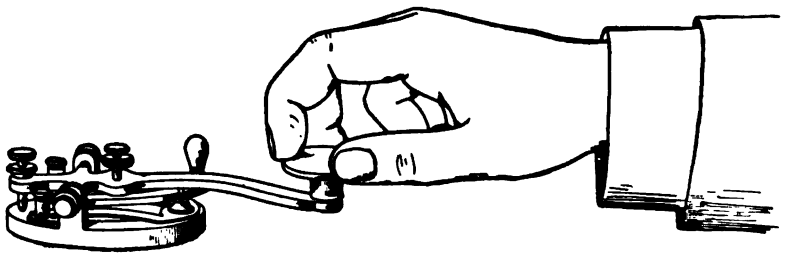

FIG. 5.

That we are able to present the alphabet in this preferred form is due to the courtesy of the D. Van Nostrand Company of New York, publishers of "Modern Practice of the Electric Telegraph" by F. L. Pope, to which manual, for details of nearly every topic in connection with telegraphy, the student is referred.

In this connection it may be of interest to state that the Morse Code, in the form in which it is now used, is the work of Alfred Vail of Morristown, N. J., and that in the selection of the signals for the different letters he was aided, so the story goes, by a chance visit to a printing-office, where he noticed that in the type cases the size of the different compartments was determined by the frequency of the use of the letter.

The attention of the learner having been called to the relative time values of the elements which go to make up the signals, he is now in a position to attempt for himself the making of them, and to take his first step as a sender. His instrument for this

purpose is the key, with regard to which it has already been explained that it is merely a convenient device for the admission and non-admission of the current to the electromagnet of the sounder, according to a prearranged code. A suggestion as to the manner of holding the key can be gained from the cut (Fig. 5) given herewith. In it will be noticed the thumb pressing lightly upward against the rubber knob, the fore and second fingers curved, their tips slightly embedded in the knob, the wrist kept well above the line of the lever. This illustration, long familiar to telegraphers from its use in advertisements, and known among them as the "Catlin grip," is not intended for exact imitation. As in the case of handwriting, individual proclivities will assert themselves; but if the learner infers from it how to gain a firm command of the key, without cramping the fingers and forearm, he will have learned all that the text-book or a teacher can tell him.

At this stage some learners simply place the code chart before them and beginning at A, with its dot and dash, plod through the entire alphabet; then back and forth over the same ground, until they have obtained a certain mastery of the signals; and many good operators have learned in just this way. The writer has heard Mr. James D. Reid, "the father of telegraphers," relate that even on his way to assume his first position he re-enforced his limited practice by tapping out the alphabet with a pencil or a knife on the window of the railway coach or on the arm of a seat. But it seems more in keeping with up-to-date methods of instruction pursued in other branches to give to the exercises now to be entered upon a growing and developing character. With this end in view the different combinations of dot, space and dash are classified and arranged in six different modes—the signals for letters, figures, and common punctuation points only being considered at present. A mere glance at the chart will indicate to the eye the differences already noted in the lengths of the dashes; the letter L is represented by a dash twice as long as T; and the signal for a cipher is a dash two and a half times as long as T. It is as well for the beginner to observe these relative lengths; but in actual work the dashes undergo some shortening without danger of error.

1. Dot only, . E .. I ... S .... H ..... P
2. Dash only, — T —— L —— cipher — — M — — — 5
— — — — paragraph
3. Dot preceding the dash, . — A .. — U ... — V .... — 4
. — — W
4. Dot following the dash, — . N — .. D — ... B — — .. 7
— .... 8 — — . G — — — . exclamation
5. A combination of (3) and (4) . — . F — . — . J — . — K
.. — . Q . — .. X . — — . 1 .. — .. 2 ... — . 3
— .. — 9 . — . — comma .. — — .. period
— .. — . interrogation
6. Dot and space, .. . C . . O . .. R .. .. Y ... . Z . ... &

The method to be followed by the student looks to the repetition of the signals for these letters and characters, first in direct order as given, and then in reverse. In this way his work is graduated, and his ear will soon become accustomed to the difference as the elements increase or decrease. Especially is this true in regard to the first mode; and in connection with the second it is to be noticed that while the dot always has the same time value, the dash, as already stated, has three different values, as indicated by the length of the lines for T, L, and cipher in the chart. The T dash repeated gives us the letter M; used thrice, the Fig. 5, and four times, the signal for a paragraph.

The third mode includes those letters and characters in which a dash or dashes is preceded by a dot or dots. They represent the letters A, U, V, W, Fig. 4. And for mode four we have a reversal of the elements in the preceding one; dot follows dash, and signals are thus composed for letters N, D, B, G, Figs. 7 and 8, and the exclamation point.

In the fifth mode the order is miscellaneous; and the more complex and difficult signals thus obtained, have assigned to them the letters least often used. They are F, J, K, Q, X, figures 1, 2, 3, 9, the comma, the period and interrogation. Last come the so-called spaced letters — of all the signals, requiring in their formation and grouping the most care. They are C, O, R, Y, Z, &; and their persistent repetition, both singly and in combinations of short words, is enjoined upon the student.

The telegraphic equivalents of all the letters, figures and more common punctuation marks having been given, attention is next called to groups of letters having signals somewhat similar.

For the letters and characters in these groups the student can find for himself the signals in the code card. He can, by inspection, determine for himself the exact difference in each case, as, for instance, in the first of the following groups A differs from I by the change of a dot into a dash.

1. I, A, S, U, H, V.
2. A, F, X, comma, W, 1.
3. U, Q, 2, period, 3.
4. K, J, 9, ?, G, 7, !

The signals for these letters and characters having by repetition become familiar to the ear, the combination of letters into words, may next be taken up. In the course of the plodding thus far pursued, the learner may begin to think that the slow analysis by the brain and the mental noting of every signal must be an irksome task. But he will find as he advances that by degrees the analysis becomes mechanical; certain sounds come to mean letters, groups of sounds, words. The real alphabet of the expert telegrapher is largely one of words; to him the clicking of the sounder is a language, and its interpretation as easy as that of speech. It is therefore with the combination of letters into words that we have now to do. And in pursuance of the progressive plan the exercises revert at this point to the order in which the signals were classified; that is, words are made up first of dot letters, then of dash letters, and so on.

1. Of the dot letters can be formed the words is, she, ship, hips, his, pies, sip, pipe, sheep.

As it is not possible to furnish many words made up exclusively of the letters in each group, single letters from other groups are here and there borrowed to make up some exercise words; as for instance, in the old-time favorites with learners, pippin and Mississippi, in which N and M belong to another group.

Exercises in words containing dot letters:

Dishes, dispel, high, dipped, Spanish, spite, shipshape, diminish, dishevel, phase, dapple, hiss, hissing.

2. Dash letters: Met, tell, till, time, mill, pellmell, metal, limit, telltale, mamma, mammal, minimum, little, time, tittle, tattle, emit, timid, multiple, multitude, dimmed, mallet, skillet, skimmed.

3. Dot before dash letters: Awe, awful, awl, law, mauve, value, valve, wave, Eva, vault, view, lava, vamp, haul, pawl, squaw.

4. Dash before dot letters: Bend, bidden, gilded, laden, dined, begemmed, dunned, dabble, nab, ban, Denbigh, Big Indian, quagga.

5. Combination of (3) and (4): Julep, jungle, junk, Fiji king, fast bind, fast find, quit, equal, quaff, quake, exit, exist, exqueen, exquisite, exhaust, skiff, piquant. Affix a k to kin and it is kink, bequeath, quaint, mujik, Ajax, Xanthine, jejune, jujube, keg, fix.

Thus far no words containing a spaced letter have been admitted. The hand and ear are thus first accustomed to the signals whose elements are separated by a uniform interval of time. By reference to the code card the learner will notice the difference in the spacing between s and c, i and o, s and r, h and y, h and z. The addition of the spaced letters makes the alphabet complete, and a number of excellent practice words omitted heretofore are now available.

6. Spaced letters: Or, err, to err is human, errant, corner, Corcyra, correct the error, eczema, corollary, co-operate, Corcoran & Co., coon, raccoon, circus, circle, cycle, bicycle, current, currant, cracker, firecracker, chronicle, coccyx, buzzard, zyrcon, correlate, physics, phantasmagoria, rhododendron, corrupt, cohesion, corduroy, road, dory, hippopotamus. There is no royal road to learning. The voice said Cry. What shall I cry? According to Sinbad the sailor, the roc's egg was enormous in size. Llewellyn, sassafras, crown, point, parallelogram, oyster, eyelet, icicle, ice-cream, puzzle, bamboozle, binocular, verdict, door, category, oracle, rollicking, moored, marooned, pirate, gyratory, circumstance, circumgyratory, paraphernalia, jiffy, effigy, equinox, quiz, Quixotic. Peter Piper's peacock picked a peck of pepper out of a pewter platter.

A few easy messages of ordinary commercial form are here introduced, attention being called to the fact that the destination occupies a line by itself. This is done so that the distributors in the larger offices can catch the "place to" at a glance.

116 B.	B N	M B	11 Paid.

RECEIVED at the ... BUILDING,.. Broadway, N. Y. July 12, 1902.

Dated Bar Harbor, Me., 12.

To Theo. Faulkner,
Jenkintown, Pa.,

Can give same room as last year—twenty-eight dollars. Answer.

(Sig.) J. S. LYMAN.

17 Kl.	M O	N D	7 Paid.

RECEIVED at the ... BUILDING,.. Broadway, N. Y. July 12, 1902.

Dated Kingston Depot, N. Y., 12.

To Mexican Gulf Agricultural Co.,
Dallas, Tex.

Arrive there Monday morning, 8.55.

(Sig.) ALLEN.

184	U D	B	20 D. H.

RECEIVED at the ... BUILDING,.. Broadway, N. Y. July 12, 1902.

Dated Mamaroneck, N. Y., 12.

To G. F. Harriman,
Pullman Co.,
Detroit, Mich.,

Empire Coupler Co. shipped car load of couplers to-day in D. L. & W. car 58,031.

(Sig.) H. M. WYATT.

In the top line the first space contains the number, and generally the call of the sending station; the second and third spaces, the signals of the sending and receiving operators; the fourth, the check. In practice the signature is also on a line by itself.

By attention to the response of the sounder as he forms the letters on the key, the learner has now to some extent familiarized himself with the *sound* of the signals as he translates their form, as printed in the code card, into the key movements necessary to produce the dot, space, and dash. Reading the signals as they are embossed on paper by a "register," except for some special uses, has become obsolete in telegraphy, so that it is with the *sound* that the learner has entirely to deal; and the signals from which he must copy are those of a hand not his own on a distant key. In this, as in handwriting, there are individual differences; and the query whether operators can recognize one another over the wire by their "Morse" can be answered in the positive. Since much depends on the initial practice in the formation of his style, the learner should, if possible, at the outset take a few lessons from an operator. That these remarks are practical and not perfunctory, the writer has personal knowledge at the present time of the contemplated removal of operators from some important circuits because of their defective sending. To aid in the formation of a correct style the signals have been presented in a graded form, beginning with the dot, which is the unit of time, passing on to the dash, then to the various combinations of dots and dashes, and lastly of dots and spaces; all with a view to their reproduction in words, phrases and sentences.

Some Faults of the Beginner. The learner may now, with key in hand held in the manner indicated, traverse once more the ground over which he has gone; but this time, he goes along with the notations of certain incorrect tendencies and faults which mark the beginner's work. He can take up those letters whose elements are simple dots, viz., e, i, s, h, p, and practice on the words already furnished, or upon combinations of his own. He will be interested at this point, and possibly encouraged, to know that some experienced operators cannot make the five dots which form the letter F, and that many more

cannot make the six dots of the figure 6. If the learner would avoid the "seven," "eight," and "ten-dot" habit, he should start in slowly, giving definite values to his dots, making the intervals uniform, until some approach to precision is reached. Avoid shortening or clipping the final dot, and make sure by actual count at first that the correct number for each character is made.

Following upon the dot mode are the four short dash characters for the letters T and M, the figure 5, the paragraph; and the elongated dash characters for L and cipher. Here, again, a tendency to shorten or lengthen the terminal dash and to space unduly the successive dashes should be guarded against. It is well to observe at first the relative time value of the dashes, but in practice the cipher and L dashes approach one another very closely without inconvenience. Occurring alone or among other letters the long dash is translated as L; among figures it is read as cipher. As between T and L, the usual inclination among learners is to make the T too long and the L too short.

In the next mode, in which the dot or dots occur first, the tendency is to separate too much the dot and dash elements. The interval between them should be appreciable to the ear, but no more. The places of these elements are reversed in the fourth mode to form the letters N, D, B, the figures 7 and 8, and the exclamation point. The first two should offer no difficulty, but B, 7 and 8 are troublesome, the tendency being to add in each case to the prescribed number of dots. There are operators who make the figure 8 for B, and a dash and five dots for 8; but no one careful of his work allows himself to fall into this habit.

Then there is that combination of the dot and dash elements which gives us the letters F, J, K, Q, A, figures 1, 2, 3, 9, the comma and the period. Of these, J and K are usually considered the most difficult, the tendency being to make a double N of the J, and the dashes of unequal length in both. The last mode brings us to the test of a good sender, in the deftness with which he makes the spaced letters unmistakable to the receiver; and he does this by such slight modifications of the space as the exigencies of the different combinations call for. The space in these characters is a prolonging of the necessary interval between the elements, and it should be just enough in excess of it to make

the letters O, C, Z, for instance, distinguishable from I, S and H; and the spaces between the successive letters of a group of spaced letters should be slightly greater than the ordinary letter space. Some unfamiliar words, such as coerce, offer such a succession of spaced letters that it is usual for careful operators to repeat the word thus: coerce? coerce — the interrogation point implying "Did you get it correctly?" It should hardly be necessary to warn the learner against the stereotyped mistake of beginners — that of going over a great deal of ground and doing nothing thoroughly. The real progress lies in correct work as one goes along, and accuracy at first in the formation of the signals will lay the foundation for safe and rapid work. The student has already been apprised, by means of three examples, what the ordinary message form is; but something more than "a learner's outfit" is needed for the exchange of messages. The point has now been reached for the consideration of the main-line circuit, to which the electric bell and the local circuit have formed a kind of introduction.

THE MAIN-LINE CIRCUIT.

As compared with the local circuit, or learner's outfit, no new

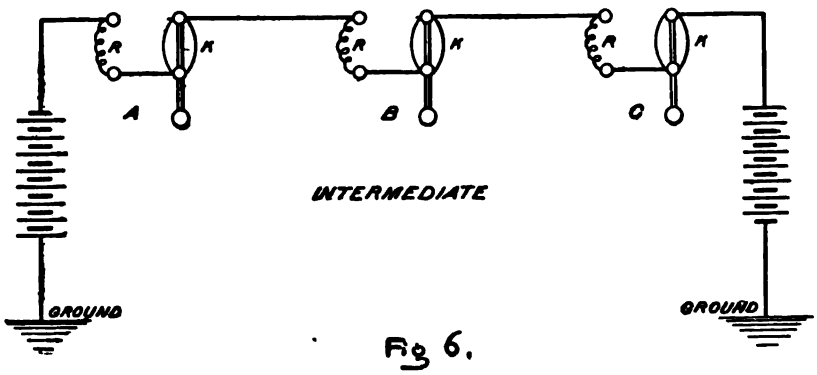

Fig 6.

principle is involved in its operation. The local circuit, with its few yards of connecting wire, has all the essential features of the longest Morse line working single; the differences are merely those of adaptation to new conditions.

First to be made clear is the difference between a metallic

and a ground circuit, as exemplified in a local and a main-line; and the location of the latter battery with respect to the the main line. Reverting now to the battery in the local circuit (Figs. 3 and 4), it will be noticed that, where the sides of the cells adjoin, the two unlike poles are connected by a short piece of wire. This, with the longer piece passing through the instruments and connecting the other poles, forms what is called a metallic circuit, because the entire path of the current is of metal. If the short piece of wire between the cells be broken in two and both ends sunk in the damp earth, the circuit will be found intact

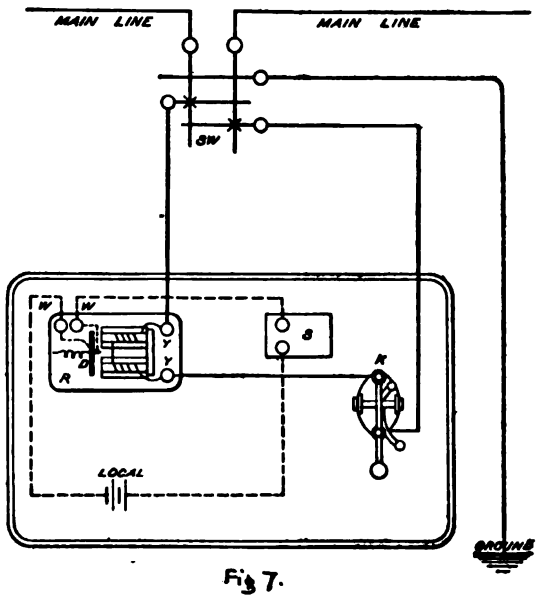

Fig 7.

as before, the current finding a path through the ground; and instead of a metallic we have what is called a "ground," or (in England) "earth" circuit. At this stage we must content ourselves with the fact that the earth acts as a return wire; the reason for it belongs to the theory of electricity. The main line is a ground circuit, not a metallic one; and the location of the main batteries relatively to the rest of the circuit is made plain in Fig. 6. In it are shown two terminal stations, each with main battery, relay R and key K; and between them is an intermediate station. The circuit here shown may be hundreds of miles in

length. The cells at each terminal are usually about 150 in number; at terminal A in the drawing the copper pole is grounded, and the zinc goes to the main line; at terminal C these conditions are reversed.

Between the terminals there may be a score or more of intermediate stations, of which only one (B) is represented in the drawing; and as its position in regard to the main line is made clear, the details of an intermediate station, hitherto passed over, are now to be described. For this purpose attention is called to Fig. 7, in which is shown, more in detail than in Fig. 2, an intermediate or way-station, with its main lines appearing at the top, its switchboard, relay, key, sounder and local circuit (dotted line) all complete. As compared with the "learner's out-

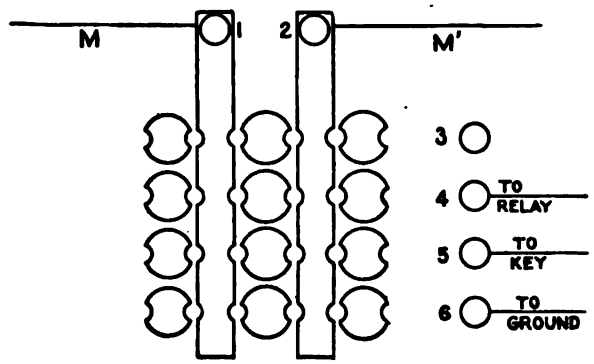

Fig. 8

fit" the additional parts are the relay and switchboard Sw. The wires marked "main line" are identical with those extending in either direction from station B in Fig. 6. In connection with relay R, Fig. 7, the dotted lines which are seen in Fig. 4 inserted in a key are replaced in the thumbscrews of the relay; and the armature and front stop of the relay are again a part of the local circuit. The coils of the relay cores, of which the thumbscrews Y Y are the terminals, form part of the main circuit, just as the coils of the sounder in Figs. 3 and 4 form part of the local circuit; but in the construction of the relay as compared with the sounder, some new features may be noted. The latter instrument is operated by a battery close at hand, for which only a few yards of wire are required; but the relay is only one of a number of

similar instruments operated by a battery or batteries through hundreds of miles of wire — a problem in which the matter of economy is also a factor. The cells of battery at each main line terminal was given as 150; but even with this number a meter inserted in the main line of an ordinary telegraph circuit would show a very feeble current. If an ordinary sounder were "cut in" on such a line, there would be no response of the armature to the opening and closing of the circuit, for the reason that the winding of its coils is not suited to the conditions. But in the relay, in order to obtain a sufficient amount of magnetism, the coils are wound with many more turns of much smaller wire. To make room for the additional turns, the soft iron cores are made longer; because of their length they are placed parallel with the base instead of standing up, and the other parts are made to correspond. The winding of the relay coils has its terminals in thumbscrews Y Y, Fig. 7; and if from one of them the main line wire is detached and tapped firmly against the thumbscrew, not only will armature D of relay R respond to the action, but all the relays on the line, be they two or twenty, open and close in unison with the non-contact or contact of the detached wire with the thumbscrew. Then because the movement of the armature of the relay opens and closes the local circuit of each and every relay along the line, the sounder in each local circuit moves in unison with the home relay — a result brought about by merely tapping the thumbscrew of the home relay with the main line wire temporarily detached from it. But the detaching and tapping method has been resorted to only to emphasize for the learner the essential features of a telegraph circuit. In practice the tapping is done much more conveniently with the key, with whose use the learner is presumed to be already somewhat familiar. And as he either has one in his possession, or the use of one, he can examine its construction for himself, so that a description of it here is unnecessary. With the key in the main line circuit to do the work done by detaching the wire from the relay, it is plain that all the instruments in the circuit can be controlled by the movements of the key; when the operator opens the key by moving the curved arm from under the spur (see Fig. 4), all the relays instantly open; when he depresses the lever they all as instantly close. This

result is possible because of the velocity of the current — the time consumed in traversing five hundred miles being inappreciable. It should now be plain to the learner how it is that the control of a key at any point in the circuit enables him to exchange signals with a distant station; and, in doing so, he "telegraphs" or, as the word means, writes at a distance; for telegraphy is distance writing, just as telephony is distance speaking.

Mention may be made here of a new form of key which in its construction and operation is a radical departure from the form hitherto in general use. The handling of the ordinary key for any length of time is a serious tax on the muscles of the forearm, resulting in some instances in an ailment known as "telegrapher's cramp." The new form of key was devised with a view to relieve the strain on the forearm by a form of lever which is not only initially different from the ordinary one, but admits of being instantly shifted into various positions, as the sender feels the need.

THE SWITCHBOARD.

One part of the apparatus of a way-station remains to be described; it is called the "switchboard," and is usually secured to the wall over the operating desk. It enables the operator to change the arrangement of the wires leading from the desk with respect to the main line, and to the ground. It is simply a board of well-seasoned wood, fitted in front with metal strips running vertically and terminating in thumbscrews; horizontally across the board are rows of small circles of metal, called discs, whose stems pass through the board, at whose back each row is connected together with a wire terminating in thumbscrews in front and at one side of the board. The strips and discs are so constructed with reference to each other, that connection can be made between them by a metal peg having a short handle of rubber. The switchboard is seen in position in Fig. 7, but is reproduced on a larger scale in Fig. 8. The different rows of discs (each row having a connecting wire at the back) have their terminals in the thumbscrews 3, 4, 5, 6, of which 4 and 5 make direct connection with the relay and key, and 6 makes connection with the ground. Suppose the way-station to be between New York and Albany;

let M represent the main line from New York, making connection with the thumbscrew 1; and M′ the wire to Albany connecting with 2. Look briefly at a few changes in the connections that can be made by means of two metal pegs. Suppose each of the discs in a given row to be numbered as shown on the right of that row. Connect with pegs 1, 3 and 3, 2. In this case the current would simply pass from bar to bar across the middle disc 3 without affecting the instruments at all; and in this position of the pegs they are said to be "cut out." Move the peg in 1, 3 to 1, 4 and the main line circuit is open because there is connection only between discs of the same row. Move the peg in 3, 2 to 5, 2 and the current has to pass through key and relay in going from one upright bar to the other, and the apparatus is said to be "cut in." The drawing represents the switchboard in its simplest form, and the operations indicated are the most ordinary; but if the learner will bear in mind that the discs are connected with each other only in straight lines across the board, he can trace out for himself other peg connections of discs and bars and the changes they bring about in the circuit. For instance, discs 6 all connect with the ground. Remove the peg from 1, 4 to 1, 6 and from 5, 2 to 6, 2; the wire from both directions is now grounded, with the result that there are now two independent circuits—one in each direction from the way-station whose operator could now work with either New York or Albany, but the stations named would be cut off one from the other. Restore the pegs to their original position in 1, 3 and 3, 2, and the terminal stations can work with each other, but the way-station is once more "cut out." This is the position in which the pegs should be placed when the operator leaves the office, or during a thunderstorm. But for the latter incident there is generally arranged a "cut out" outside the office. Many intermediate stations have more than one wire and switchboard to correspond, and it would be possible to fill pages with the combinations that might be effected; but sufficient explanation has been given to indicate the method which, when once understood, can easily be extended and applied to suit larger needs.

In the care and adjustment of his instruments, the operator should see that the local points of his relay and the points of his key are clean; he should be on his guard to see that the armature

of his relay or sounder does not hit upon the soft iron of the cores. A good way to assure himself of this is to pass a piece of paper at times between the armature and the core. Instructions in the care of the local battery are now in order; but they differ with the kind of battery used, and are usually furnished in the book of rules of each company.

The purpose up to this point has been to give the reader an idea of the apparatus employed in telegraphy. It has been emphasized thus far that the essential features of the local circuit, viz., battery, electro-magnets, and connecting wires, are all reproduced in the main circuit, the differences being only those of adaptation to new conditions.

With this statement a reversion is now made to the practical —to the matter of the exchange of messages, of which some examples of the ordinary form have already been given. The greater part of the business handled by the commercial companies is of the kind exhibited; but the work of the operator would be easy if it consisted in exchanging only such messages as the samples. In addition to the ordinary form, there are those known among telegraphers by the following terms: Wire, service, forwarded message, repeated back, government, grain, transfer, cipher, number group, circular, C. N. D. (Commercial News Department), marine, and railway D. H. Then there is the press service, making use, in some cases, of fixed forms for a baseball score, golf score, and the like. Of ordinary press matter the volume on certain occasions, such as a presidential convention, is great. At the present time much of the press matter is handled on wires leased from the telegraph companies by the press associations, and their carrying capacity is increased by the use of a code which enables an operator to transmit as fast as an expert typewriter, at his highest speed, can copy. Of code telegraphy, some details will be given later on. In addition to all these the art has been specialized by railway companies in the movement of their trains and traffic, also by brokers and large commercial houses, to such an extent that even an expert operator must serve an apprenticeship in order to fit himself for the rapid work in these specialized forms.

Of the different kinds of messages just enumerated, the first two designations are self-explanatory, the former having to do

with the assignment, arrangement, and cross-connection of wires; the latter with the forwarding, re-addressing, and delivery of telegrams. Service messages have to do with the movement of the despatch from the customer to the hands of the party addressed, and, if errors have been made, with their correction.

The following are examples of this form of message:

Marietta Pa ofs.

Give full address Oswald Denberg. We fail to locate your msg date signed National El. Co. S. Y. S. (sig) Munn, New York.

The use of abbreviations will be noted; and for some constantly recurring phrases, such as "see your service," only the initials are used. "Give better address" is similarly represented by G. B. A.

Munn, N. Y.

Pls D. W. C. from original yours today Carnegie Steel Co. signed Union National Bank, A. L. Dignam Cashier. Same reaches us dated Waterbury Conn.; Carnegie say think should be dated Watertown N. Y. Advise my care.

(sig) Phila., Pa.

In this case a "duplicate with care" is requested.

An extra-date message is one that has been received by mail at, say, Albany office; or, having come over another line, has been handed in to be sent forward, and takes this form:

116A Bn Mo 15 Paid

Berlin, N. Y. Oct. 26, via Albany Oct. 26

Adam Brown,

Bridgeport, Conn.

Have been unexpectedly detained. Meet me next Monday at ten. H. Brosnan.

In this case the five words "Berlin N. Y. Oct. 26" are added in and charged for as part of the message. It is customary when the party to whom a message is addressed has left town, to forward it to a given address, in which case the forwarding station, with the word *via*, appears in the date, and the originating station and date are charged for, the same as in the example just given.

Occasionally the sender of a message, to insure its correct-

ness, requests a repetition, in which case the words "repeat back" are inserted in the check and included in the count. For such repetition a charge of a rate and a half is made. A "night message" does not differ in form from the examples of paid messages already given, except that it is always copied on a blank printed in red ink, and in the check is inserted the word "night," which is not counted. In all collect messages, whether day or night, the word "collect" is counted as if part of the body of the message.

Government messages are exchanged between the officials of the United States government and its employees, and differ from the ordinary form in that the address and signature are counted as part of the body of the message, thus:

197W Kn Mg 28 Paid Gov't

Washington, D. C. June 24

Col. H. K. Ames

Memphis, Tenn.

Forward to New Orleans all the tents and rations you can spare in aid of the flooded district.

(sig) E. M. Harrison,

Commissary General.

The text or body of this message contains only seventeen words; but the count of every word in the address and signature makes the check twenty-eight.

A prominent feature of commercial telegraphy at the present day is the facilities provided for the quick interchange of messages between Produce, Stock, and Cotton Exchanges in cities remote from each other, the circuit arrangements being such that the members of these bodies can carry on their trading with a celerity and correctness that leave little to be improved upon. Many of these traders have their own private wires; but the greater part of this class of business is carried on by the New York Produce Exchange with the different grain centres, such as Buffalo, Toledo, Detroit, Chicago, Duluth. In the forms of messages hitherto given each message is preceded by its number, the signals of the sending and receiving operators, and the check. In the exchange of grain orders all this, with the exception of the number, is dis-

pensed with. To show the difference in usage between the ordinary and the exchange form, a message is given in both:

B123 Da Mo 7 Paid

Ex Chicago, May 18

J. C. Ladenberg,

New York.

Sell five July corn at sixty half.

(sig) M. J. ALLEN.

In practice this would be transmitted in abbreviated form, thus:

B186 7 Pd.

Ex. J. C. L. Sell etc. (sig) M. J. A.

Such work, of course, calls for experience on the part of the operator and great familiarity with the names of his patrons; these being granted, the volume of business that can be handled during exchange hours is large.

There has been evolved in connection with the telegraph service a great convenience to the business community in the order by wire to pay to one party money deposited by another — a transaction possible between cities on opposite sides of the continent. The instrument of this exchange is a message called a "transfer," of which the following is the common form:

B171 Dq Rn 17 Free

Hartford, Conn. June 19

J. D. Mallory,

Henderson, Texas.

Pay to N. D. Hilliard, Hotel Baldwin, gilt bald edgeways from E. L. Adams, Jr., Hartford. Vigilant

(sig) H. N. Tallman,

Transfer Agent.

It is a curious fact in connection with the "transfer" that in place of the very commonly used D. H. for "deadhead" in the check, the word "free" has always been retained. It is said that the use of this rather grim phrase with the meaning "no charge" dates as far back as the Roman times, when free admission to the circus and the theatres was gained by the presentation of a carved death's head furnished by the authorities.

THE CIPHER MESSAGE.

In the above message it will be noticed that the amount to be paid is indicated by words without meaning to the outsider; and it concludes with "Vigilant," which is understood to mean "identification is required." The "transfer" is, therefore, in part a cipher — a form of message much in favor among patrons of the telegraph. It involves the representation of a word or phrase by a word arbitrarily chosen, and therefore understood only by those concerned; and this is very nearly the dictionary definition of the word "cipher" used in the sense of a secret writing. Its use in telegraphy serves the double purpose of economy and secrecy; and incidentally some forms of it greatly tax the patience of the operator. As the meaning of the cipher is the concern only of the correspondents, there may be as many systems as there are patrons; but among business men the phrases in common use became so numerous that cipher-making itself became a business. At the present time quite a number of systems are in use; so that, to carry on a secret telegraphy, the patron needs only to buy two copies of any preferred code — one for himself, and one for his correspondent. As the words representing the different phrases are generally chosen arbitrarily, any number of English words chosen at random might be taken to form the text of a "cipher" message. But portions of two or three with fictitious addresses, are here given to bring the learner into touch with the reality.

B67 Ha Ks 10 Paid

New York. June 19

L. M. Hazeltine,

Boulder, Col.

Metemperic entire peasoup velvetleaf bondmaid eighteen birthsongs thalarctos each periwig.

(sig) Alpha.

B68 Pq An 11 Collect

North Adams, Mass. June 21

C. K. Thurber & Co.

New York.

Admixed unaided unbias aleak unapplied fetch andiron marauding maroon hairpin.

(sig) E. M. Seymour.

In this last, as in all messages similarly checked, the word "collect" is counted. Of the more difficult forms of cipher that in use by the large business houses of the West furnishes two examples:

C18 Mo Ns 20 Paid
Kansas City, Mo. June 21
L. M. Wetstein,
New York.

Molucris morbescunt desque cow dexterous demulsion facial gildos holzstoss hoodwink hymnifero hamaux marandara vetader no vetachtig motandos fatichera komplot salami.

(sig) Roburn.

D21 Aj So 15 Collect
Indianapolis, Ind. June 24
R. A. Clarkson,
Middletown, N. Y.

Asander unbespeak umsetzbar unbeing boneless maragnon monarch cervelat disallowed each car alamoth arrodeth absorb.

(sig) Schievelin.

Quite commonly these messages contain several hundred words, and no knowledge of English or of any other language is of much aid to the receiving operator; he must watch for each letter, and pen or typewrite the signals as they arrive. It should be apparent at a glance what an indispensable aid to this work the typewriter is. By means of it these unintelligible words are copied in a manner that makes them unmistakable to the reader, and the receiver has no need to resort to the old expedient of "writing in" the Morse characters under the letters imperfectly formed by the pen.

The Cable Message. The high tolls charged for cable service makes the use of cipher in their composition very common. The address and signature of each message is counted, and the former is often transmitted as a cipher word, which is duly registered for reference when needed; for instance, Havicam, London, might stand for Haviland, Campbell & Co., at any address in that city they chose to give. A single example only of a cable message need be given, as the one form is quite generally followed.

52 Yv Kn Duluth 10
Richfig,
Rotterdam.
Ascanilota apilatori makobojoss Koln luhoto
schizandra pythao (sig) Blockland.

Several of the words, it will be noticed, contain just ten letters. This is the permissable limit for one word; if exceeded, the word is counted as two, except in case of the destination, as Constantinople. The correct handling of cables involves many matters of detail in regard to the "count" which requires some little practice to master properly.

A unique form of cipher deserving of mention here, makes a message to consist entirely of groups of figures, usually five in a group and in this form: 17641, 75689, 84356, 09543, and so on through hundreds of groups. For the nought beginning the last group the signals for TW — dash, dot, dash, dash — are sometimes used. This form of cipher seems to be much used in correspondence between the different governments and their representatives and agents.

The circular message, as its name indicates, has a number of addresses with a common text, or body. For this form the senders generally avail themselves of the night-rate service. Except for the plurality of the addresses, each one of which in sending is separately numbered, it does not usually differ in form from the ordinary message.

The "C N. D." The Commercial News Department message is as unique in appearance as it is different in form from the others. The department is an agency for systemized and detailed advice in matters of commercial interest as they transpire in the different exchanges, and in sporting matters to individual patrons and customers. For transmission by the operator the message is usually written either on a pink blank or on a sheet of yellow manifold. One such, picked up at random, reads: "Add Charleston. Quiet 8¾ Sales 50 . . . 2.31" This is a quotation of cotton, and the time when written takes the place of the signature. Another reads:

"Detroit close 2.25
"Dw 84b Red & m 81 N 76 U 75½ . . . 1.15"

To the initiated this means: Cash wheat 84 bid; Red and mixed 81 July 76 September 75½. 1.15 is the Detroit time; 2.25 is the time received in New York. Another, addressed to a summer hotel on Long Island, reads:

"Stocks A81⅝; St 175; MP109⅝; USS37⅞; U 105 . . . 10.16 A.M.," in which A stands for Atchison, Topeka and Santa Fé; St for St. Paul, and so on through the list.

These brief examples give the merest hint of the traffic of this elaborate system; and so diversified are its forms it takes weeks and in some cases months of training to make even a skilled operator master of the service.

The Marine Message. The natural interest of the friends of those at sea in the sighting of their ships, and their desire to know the probable time of their arrival at the dock in New York, led to the organization of the Marine Department, which, on payment of a certain sum, furnishes the information in the following form:

Marine Department, New York, June 2.

George Homer, 351 West 14th St., New York.

Steamer "Columbia" will arrive, unless detained at quarantine, about 6.30 P.M. (Sig.) Manager Marine Department.

This service is almost as old as the telegraph itself, and it remains to be seen how far the wireless system will modify it. It is certainly in this direction that the latter system should first make itself felt.

Of the railway D. H. a short example has already been given as one of the three specimens of the ordinary message. Its marks are the use of initials and groups of figures in which each digit is counted as a word. They are frequently of great length, and require some care in copying in order not to lose the count.

Abbreviated Telegraphy. A notable development of the art in connection with the fast-speed press work involves the use of abbreviations according to a system, and is known among the craft as Code Telegraphy. It was always more or less the custom among press operators to abbreviate familiar and frequently recurring words and phrases when sending to experienced mates; but the introduction of the typewriter gave such impetus to the art that a codified Morse, at the present time, is not far behind the speed of ordinary speech. Beginning with the Morse alphabet,

figures and ordinary punctuation marks, the code system first provides an extended system of punctuation covering all the characters and marks that commonly occur in print, as follows: (See page 34.)

For an apostrophe the signal is the same as that given in this

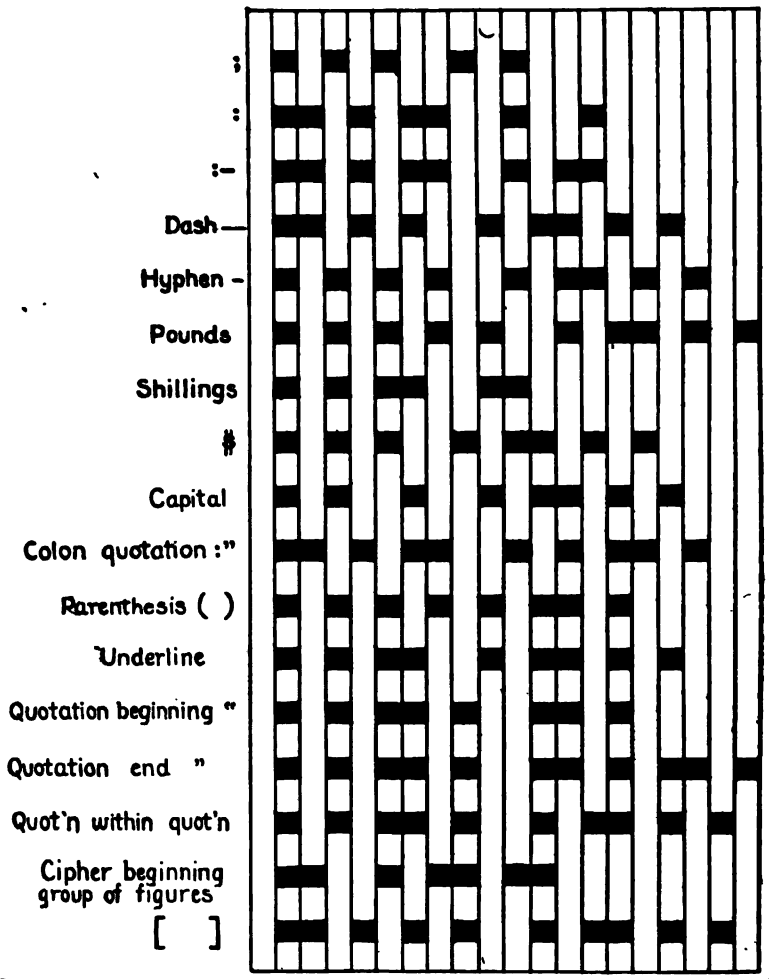

chart for quotation within a quotation; a parenthesis begins with Pn, and ends with Pq; a fraction, as $\frac{3}{4}$, is transmitted 3e4; a decimal, as 89.92, 89dot92; omitted words are indicated by a series of x's; and in sending one or more lines of verse a paragraph mark (– – – –) closes each line.

The system in general use among operators is the Phillips Code, from its inventor, Mr. Walter P. Phillips, general manager of the United Press; and in its arrangement it advances of course from the simple to the complex. Single letters are first made to represent common words and phrases: B, be; C, see; F, of the; K, out of the; Q, on the; and so on through a list that need not be reproduced here, because the entire code can be purchased in book form and contains, besides the code itself, hints for the memorizing and proper use of it. The single letter list is followed by the two-letter and three-letter contractions; and the learner will think it is a far cry from the jog trot of the ordinary text to such expedients as "fap" for "filed a petition," "sak" for "shot and killed," and "sbl" for "struck by lightning." The typewriter alone makes the use of such abbreviations possible. In order that beginners may catch the spirit of the system, the following exercise is written in the code text and then given in full:

"Bt Lafa Plc is smhw Lafa Plc stil. Its trnsfmatn into chp lodgmts is gradl tho su. T sieg gos stedly on, bt t bsiegd hv n yet sucmbd. Ey y t hansm cariags tt rol up & dwn its aves gro fuer and fuer si ey y its pavmts worn bi t fet o ded & gon Nikrbokrs r m fqd bi shaby Germns or slatrnly Italns."

"But Lafayette Place is somehow Lafayette Place still. Its transformation into cheap lodgments is gradual though sure. The siege goes steadily on, but the besieged have not yet succumbed. Every year the handsome carriages that roll up and down its avenues grow fewer and fewer; every year its pavements, worn by the feet of dead and gone Knickerbockers, are more frequented by shabby Germans or slatternly Italians."

SECTION 8.

THE TELEPHONE.

In order to understand the operation of the telephone, it is necessary, first of all, to understand the principles underlying the production of sound, or of acoustics. Sound is produced by vibrations in the air set up by whatever may be the cause producing the sound. These vibrations strike the eardrum, and the sensation of sound is conveyed to the brain. The pitch depends upon the rapidity of the vibration, the loudness upon the amplitude, and the quality upon the form of the vibration.

The simplest sort of vibration is that set up by a musical tone, and to give an idea of the rapidity of vibrations for a specific case it may be stated that the musical tone known as middle C is set up by 256 vibrations per second. The vibrations set up by the

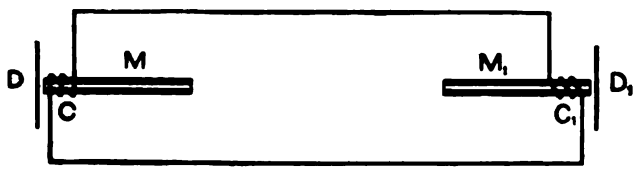

Fig. 1.

voice in speaking are of a much more complex nature in every way, and on this account the earliest telephones could reproduce musical tones, but could not transmit speech.

The earlier telephones served to transmit and reproduce the vibrations of the voice by means of electromagnetic induction. A typical telephone circuit in its simplest form is shown in Fig. 1. There are two similar instruments, one at each end of the circuit; we may consider one the transmitter and the other the receiver. M and M_1 are two permanent bar magnets on the ends of which are coils of fine insulated wire, C and C_1. In front of the mag-

nets are thin elastic disks of sheet iron, D and D_1, commonly known as the diaphragms. Let us consider the left-hand instrument the transmitter, and the other the receiver. The permanent magnet M sets up a certain number of magnetic lines of force through the coil C, and as the diaphragm D offers a path of lower magnetic resistance than the air, many of these lines pass through it. When we speak close to the diaphragm D, the air vibrations cause the diaphragm to vibrate. As it approaches the magnet M more magnetic lines pass through the diaphragm, and when it recedes fewer lines pass through it. This action alters the number of magnetic lines which pass through the coil C, and hence alternating currents are induced in it which are proportional in strength to the rate of change of the number of lines.

These currents also pass through the coil C_1 at the receiving end of the line, and according to the direction in which they flow around the magnet M_1, alternately add to or tend to neutralize its strength. When the current strengthens the magnet, it causes it to attract its diaphragm D_1, and when the current decreases the strength of the magnet, the diaphragm moves away. In this manner the diaphragm at the receiving end is made to vibrate in exact

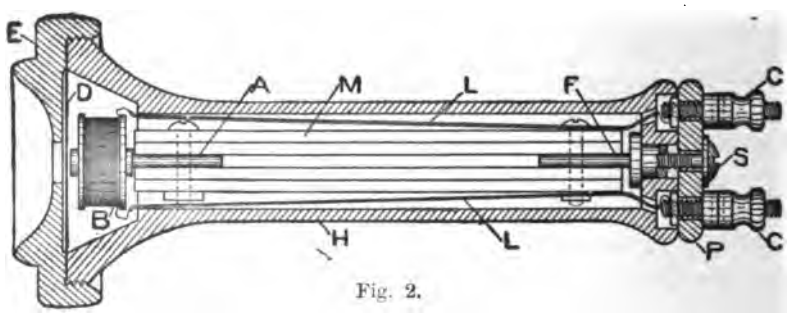

Fig. 2.

unison with the one at the transmitting end, and thus similar vibrations of the air are set up, reproducing the sounds spoken into the transmitter.

The above arrangement has been somewhat modified in the telephone of the present day, and it has been found more convenient to have a separate transmitter at each end of the circuit. The transmitters now in use operate on entirely different principles, but the receiver is essentially the same.

Receivers. There are two common forms of receiver: the single-pole and the bipolar type.

A single-pole receiver of the Bell type is shown in section in Fig. 2. It consists of a hard rubber case H, in which is placed the laminated or compound bar magnet of steel M. This magnet is composed of two sets of bars separately magnetized; clamped between them by means of screws is the pole piece of soft iron A at one end and the block F at the other end. Upon the pole piece is placed a coil of fine insulated copper wire B; connection being made from it to the binding posts C C by means of heavy wires L L. The binding posts are attached to the end piece P, which is held in place by the screw S which threads into the block F, and thus serves also to keep the magnet in position. The cap E screws to the case and supports the diaphragm D, which is a flexible disk of soft iron. The diaphragm is placed a short distance in front of the pole piece of the magnet, and the portion directly opposite it is free to vibrate.

This instrument is being supplanted to a great extent by the bipolar receiver, which differs from the single-pole receiver in that the permanent magnet, instead of being straight, is constructed upon the horse-shoe principle. This brings both poles in position to act on the diaphragm, giving increased strength of field, and consequently making the instrument more efficient. A soft-iron pole piece is secured to each end of the magnet, and a coil of insulated copper wire is mounted on each pole piece.

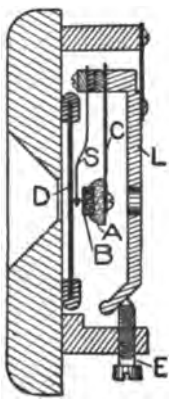

Fig. 3.

At the present time the single-pole receiver is sometimes used for local work, while the bipolar receiver is employed both for this and for long-distance work. There is also another form of receiver known as the watch-case type, which is used to some extent for desk sets and at the exchange switch-board.

Transmitters. The type of telephone just described was originally used as the transmitter as well as the receiver, and for short distances, in which the line resistance was small, gave fairly good results.

It is now the practice to use this instrument as the receiver

only, and to use a different form of instrument, together with a battery, for the transmitter. The action of this transmitter depends upon the fact, that if the resistance of a circuit is increased, the current will be decreased, and if the resistance is decreased, the current will be increased. This variation in resistance is produced by varying the pressure between one or more carbon contacts. If the pressure is increased, the resistance is decreased, and if the pressure is decreased, the resistance is increased.

There are three types of transmitter: in the first but one carbon contact is used for varying the resistance, in the second several contacts are used, and in the third granular carbon is employed, thus giving a very large number of contacts.

The Blake transmitter, a section of which is shown in Fig. 3, is an example of the first type. This instrument, in common with all other transmitters, has a diaphragm D, somewhat similar to that of the receiver. This is supported in a rubber ring, and is held in place by two damping springs not shown in the cut. Mounted upon a light spring S, and resting against the back of the center of this diaphragm, is the front electrode, which is a platinum pin. Directly back of this piece of platinum, a carbon button B, which forms the other electrode, is supported by means of a spring C, so adjusted that the carbon button bears lightly against the platinum pin. The tendency of the spring S is to press the platinum pin away from the diaphragm; but this is overcome by the stiffer spring C which bears in the opposite direction, and so keeps the platinum in contact with the diaphragm. The electrode B is mounted in a comparatively heavy socket of brass A. Both electrodes can move freely with the vibrations of the diaphragm; but the carbon, on account of the inertia due to the weight of the brass socket, moves more slowly than the other. Any vibration of the diaphragm will, therefore, result in a variation of the pressure between the two electrodes, and thus vary the resistance of the contact.

The two springs S and C are insulated from each other, and the current goes to the contact point by means of one spring and leaves by the other. The adjustment of the pressure is effected by means of the screw E, which bears against the lever L.

This transmitter is quite satisfactory for lines of moderate

length, and is used to some extent at the present time. It is, however, somewhat difficult to keep in adjustment, and is not well adapted for long-distance work.

The second type of transmitter mentioned is not much used in this country, and a description need not be given.

The most common form of transmitter, and the one which is rapidly replacing all others, is the Hunnings or granular carbon type. This, as originally planned by its inventor, consists of two insulated plates of conducting material which form the electrodes of the transmitter, the space between them being filled with granular carbon. The general form of this instrument is shown in Fig. 4. D is the diaphragm of metal or carbon which is clamped between the body of the case C and the cap A by means of screws. Another conducting plate B, of metal or carbon, is placed in the back of the case, and the space between D and B is filled with granular carbon. The conducting plates D and B form the electrodes or terminals of this transmitter. When the diaphragm is spoken against, it of course vibrates, and thus varies the pressure upon the numerous contact points of the granular carbon through which the current must flow to pass from one electrode to the other, and thus the resistance is varied as in the Blake instrument. Larger currents can be used with the Hunnings type of transmitter than with other sorts, and it has the further advantage of allowing a greater variation of resistance.

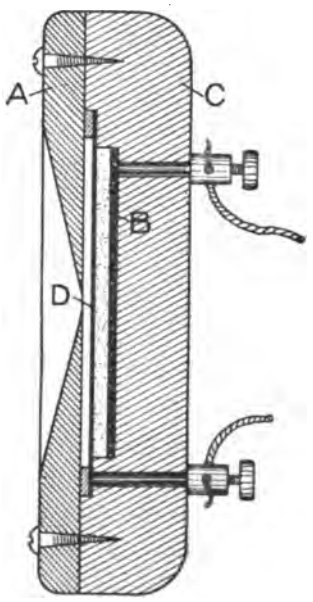

Fig. 4.

The transmitter which is used almost entirely at the present time is known as the "solid back," being a modification of the Hunnings type just described. The case, which is of metal and hollowed out to contain the working parts of the instrument, is enclosed by a brass cover, which also carries the mouth piece. The metal diaphragm is supported in a ring of soft rubber

attached to the back of the cover. The electrodes are enclosed in a metal chamber which is lined with insulating material. This electrode chamber is secured by means of a set screw to a metal bridge which is attached to the back of the cover by means of screws. Both electrodes are of carbon, being in the form of discs somewhat smaller in diameter than the containing chamber. The space between the electrodes is filled with granular carbon as is also the space between the circumference of the discs and the insulated walls of the chamber. The rear electrode is mounted upon a brass disc which is screwed to the back of the chamber, thereby holding the electrode securely in place. This electrode being in metallic connection with the containing chamber, is in electrical connection, through the bridge and cover, with the frame of the transmitter which thus becomes one of the terminals.

The front electrode is also backed by a brass disc which is attached to the metal diaphragm of the transmitter by means of a stud which passes first through a mica washer that serves to enclose the electrode chamber, and then through the center of the diaphragm. This stud is fitted with two threads, upon one of which is screwed a nut which clamps the mica washer to the electrode, and upon the other two nuts which clamp the electrode to the diaphragm. A brass collar, which screws to the periphery of the electrode chamber, binds the mica washer securely against it. Connection is made to the front electrode, which is the second terminal, by means of a fine wire brought out to a binding post mounted upon an insulated block.

The vibrations of the diaphragm are communicated directly to the front electrode, which thus varies the pressure upon the mass of granular carbon and consequently serves to vary the resistance. Two damping springs rest against the diaphragm, thus keeping the amplitude of its vibrations within reasonable limits, and checking them as soon as they have performed their part, leaving the diaphragm ready to obey the impulses due to the succeeding sound waves.

This transmitter operates in a very satisfactory manner; excellent contact is made between the carbon electrodes and the particles of granular carbon. Packing of the granules is pre-

Telephone Switch Board for 600 Lines.
Courtesy of the Sterling Electric Company.

vented on account of the space between the periphery of the electrodes and the inner circumference of the chamber, which contains granules that do not become heated by the passage of the current. Hence when the granules between the electrodes become heated they can expand into this portion.

The transmitters of this type manufactured by different companies vary slightly in minor details of construction, but all operate upon practically the same principles.

Simple Telephone Circuit. The earliest form of telephone circuit consisted simply of two Bell receivers connected in series. The one which was being used as a transmitter served as a very small generator which sent alternating currents over the line, and these acted upon the instrument at the other end of the circuit, which was, for the time being, used as a receiver.

After the invention of the carbon transmitter the circuit consisted of a transmitter and receiver at each end of the line, together with the batteries which furnished the power, all connected in series. This arrangement did not give satisfactory results for many reasons, but the use of the induction coil overcame the difficulties previously met with.

A typical circuit with the induction coil is shown in Fig. 5. Here T is the transmitter, B the battery, P the primary and S the secondary of the induction coil, and R the receiver. The primary

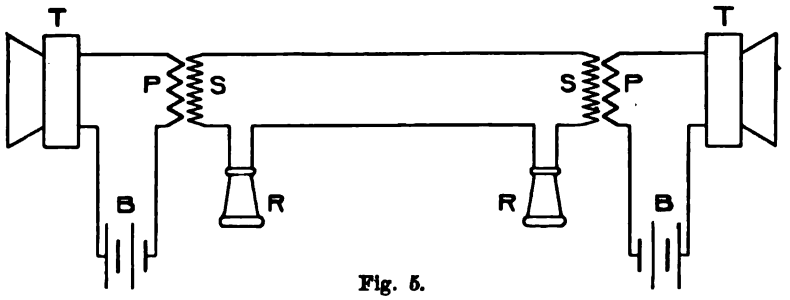

Fig. 5.

circuit contains the transmitter, batteries, and primary of the induction coil, while the secondary circuit contains the receiver and secondary coil. When the transmitter at one end of the line is spoken into, the resistance of the primary circuit is varied, and this in turn varies the strength of the current passing through the

primary of the induction coil. Consequently alternating currents are induced in the secondary coil which pass over the line and act upon the receiver at the opposite end.

The action of the induction coil has already been described. The coil used in telephone work has a core made of soft iron wires. Upon this is wound the primary coil, consisting of a comparatively small number of turns of coarse insulated copper wire, and outside of this, and carefully insulated from it, is the secondary coil in which are a great many turns of fine insulated copper wire. Without the induction coil, it is probable that the long distance telephone in its present state of perfection would have been impossible. Its use allows the resistance of the circuit in which the transmitter acts to be very small; with the result that the effects of the variations in resistance due to the transmitter are comparatively large. This low resistance also permits a larger current to flow with a given number of cells of battery. The electromotive force of the secondary current is high, thus being well adapted to overcome the high resistance of the receivers, secondary coils, and line wires. Still another advantage lies in the fact that if the transmitter were connected directly in the main circuit, its effect would be to cause the current in the line to vary in strength but not to change in direction. In other words, the current would be undulating but not alternating. However, better results are obtained if the current which actuates the receiver is alternating, and this is of course the nature of the current in the secondary of the induction coil.

Batteries. In telephone work the batteries are required to furnish current for only short periods of time, and the Leclanche cell is admirably adapted for the purpose. It requires very little attention and will furnish a comparatively large current for a short time. Moreover, although these batteries polarize in a short time if kept on a closed circuit, they recover very quickly when the circuit is opened.

The Fuller cell is also used to a considerable extent. In this cell the plates are zinc and carbon; dilute sulphuric acid is the excitant, and either bichromate of sodium or bichromate of potassium may be used as the depolarizer. The zinc is placed in a porous cup, in the bottom of which is a small quantity of mercury

which serves to amalgamate the surface of the zinc and thus prevent local action between the zinc and the impurities which it contains. This cup is then filled with a solution of sodium chloride (or common salt) dissolved in water. In the battery jar is the solution of dilute sulphuric acid and bichromate of sodium or potassium. The porous cup is put into the jar, and the carbon suspended through an opening in the cover which fits over the jar. This cell is excellent for telephone work; it has a high voltage, low internal resistance, and does not deteriorate on open circuit.

The gravity battery, already described, and the storage battery are used in telephone work when constant service is required. Dry cells are also used extensively, particularly in intercommunicating sets, on account of their cleanliness and convenience.

The Magneto-Generator. The above-described equipment serves to transmit and receive messages, but it is also necessary to supply some sort of calling device. The simplest apparatus for this purpose consists of an ordinary bell or buzzer operated by batteries, and this system is used commonly to-day for office sets where the distance between stations is small.

For long distances it is, however, impracticable to use this system for calling, and recourse is had to the magneto, which is described in another section. This consists of a generator having permanent field magnets and a shuttle armature which is wound with many turns of fine insulated copper wire. The armature is rotated at high speed by means of a small pinion on its shaft which meshes with a larger gear which is turned by means of a crank. This machine furnishes an alternating current, and hence it is necessary to use a polarized bell or ringer in connection with it, so constructed as to operate with an alternating current. Magneto-generators are designated by the resistance through which they will ring, being spoken of as a 10,000-ohm, 20,000-ohm generator, etc.

At the exchange it is quite common to use a power-driven magneto-generator, which may be driven from a small direct or alternating current motor. Also in some cases the motor-generator is used to supply current for ringing purposes.

Circuits of the Telephone. A complete telephone set is made up of three distinct circuits: one for the calling apparatus, one for the transmitting apparatus, and one for the receiving apparatus. The calling apparatus includes the generator and ringer, the transmitting apparatus consists of the transmitter, batteries, and primary, and the receiving apparatus consists of the receiver and secondary of the induction coil.

When the telephone is not in use the calling apparatus must be connected with the line while the transmitting and receiving circuits are both open. On the other hand, when the telephone is used for talking, the calling circuit should be opened, the transmitting circuit should be closed, and the receiving circuit should be connected to the line. These results are accomplished automatically by means of the switch-hook upon which the receiver is hung. This hook is depressed when the receiver is in place, and raised by a spring when it is removed. In this manner the desired connections are made at the proper time.

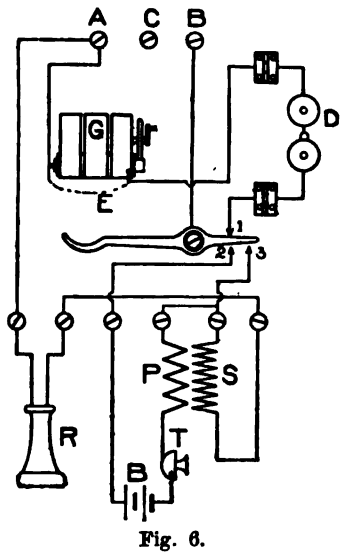

Fig. 6.

There are two types of telephone, differing somewhat in the details of their construction and connections, known as the series telephone and the bridged telephone.

The circuits of a series telephone are shown in Fig. 6. A and B are the line terminals, and C the ground connection for the lightning arrester. When the receiver is on the hook the switch is in the position shown. The generator G and ringer D are in series across the line, through contact point 1, the generator being automatically cut out by the shunt E, when not in use. When the receiver is removed, the contact at 1 is broken, and contact is made at points 2 and 3. The primary circuit is then closed on itself, while the secondary circuit, containing the receiver and secondary of the induction coil, is cut in on the line.

Below there are three pairs of binding posts, to one pair of which the receiver R is connected, to another are connected the terminals of the primary circuit containing the transmitter T, the battery B, and primary P of the induction coil, while the secondary S of the induction coil is connected to the third pair.

Connection is made to the bell through the hinges of the box upon the door of which it is mounted. It is customary to use a ringer of 80 to 120 ohms resistance with series telephones. On account of this low resistance many series telephones cannot be bridged because it would be impossible to ring a number of them in multiple. Moreover, many series telephones could not be connected in series, because, since all the ringers would be constantly in the circuit, it would be impossible to talk through them. Hence this type of telephone is used almost exclusively for city exchange work, not more than two telephones being connected on a line.

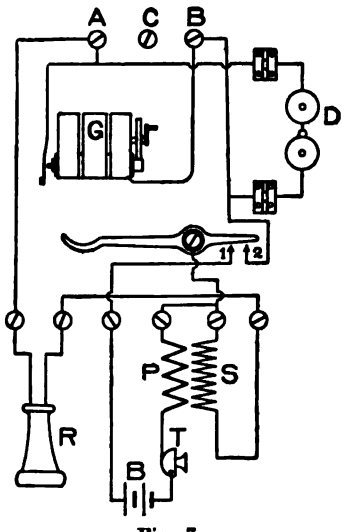

Fig. 7.

The circuits of the bridged telephone are shown in Fig. 7. The ringer coils are permanently bridged across the line. The generator is also bridged, the circuit through it being open when it is not in use, but being closed, usually automatically, when the generator is in operation. When the receiver is taken from the hook, contact is made at points 1 and 2 for the primary and secondary circuits as in the series telephone.

The permanently bridged ringer does not interfere with the action of the receiving circuit, since its coils have a resistance of about 1600 ohms, and are wound so that their self-induction is large. Thus they offer a high impedance to the currents in the receiving circuit because of the extreme rapidity with which they alternate. For this reason a number of these telephones can be bridged upon one circuit, thus forming a party line.

SECTION 9.

WIRELESS TELEGRAPHY.

THE subject of wireless telegraphy, when first presented for consideration, partakes of the nature of the supernatural in that there seems to be no tangible connection between the two points from and to which the message is being transmitted. Usage, however, accustoms the mind to many things that would, at first sight, seem strange and impossible. Take the whole range of electrical phenomena for an example. Could anything have been more uncanny to the average man of the day than the flashing of the first message by the telegraph from Washington to Baltimore? There was no tangible connection between the two points as tangibility was considered in those days. There was simply an impassive, immovable wire, and yet the pressing of the key in one place caused the message to be clicked off in another.

Then we were taught for many years that the tones of the human articulating voice could never be reproduced, and yet the telephone accomplished this impossibility, and to-day it is an every-day commonplace.

So it is in the matter of the wireless telegraph. It has not sprung into existence in a night, but is the result of long and protracted study and experimentation in the laboratories of the first physicists of the world.

In a way it may be asserted that all signaling through space without the intervention of wires or fixed connections is a species of wireless telegraphy, and such signaling includes the use of flags and the heliograph. But true telegraphy, as the name indicates, involves the use of some sort of electrical transmission, and thus materially narrows the range of the classes of signaling to which the term can be applied.

Wireless telegraphy signifies a method of transmission in which the wires of the ordinary telegraph are replaced by the air, the earth, or the ether that is supposed to fill all space, and which

is looked upon as the medium by which light, heat, and electrical waves are transmitted from the point of generation to the point of reception.

In dealing with this subject, it will be necessary to treat it partly from an historical and partly from a technical standpoint; and, in order that the conception of the principles of operation as well as the steps by which the practical details have been worked may be accurate, it will be necessary at times to apparently retrace our way instead of maintaining a strictly accurate chronological consecutiveness in all that is said.

There are two systems of wireless telegraphy that are practical, and both of which have been worked commercially. One depends upon induction for the transmission of the current, and the other upon what are known as the Hertz waves. The latter system can also be divided into two sub-systems, in one of which a beam of ultra-violet light is used as the means of facilitating the generation of the current or the action of the Hertz waves, and the other in which the waves are themselves produced intermittently in a manner to produce the signals of the Morse code that is used in ordinary telegraphic communications.

It is a curious fact that the first manifestations of wireless telegraphy were due to telephonic effects, and that the telephone played a very important part in the development of the principles by which the wireless telegraph is operated; and yet in the final form which it has reached, the telephone has entirely disappeared from the commercial instruments, though it is still extensively used for laboratory investigations.

Turning now to the induction system of wireless telegraphy, it would appear to be the most natural one along which investigations should proceed. It is well known that a current in one wire will induce another, though weaker one, in a second at a distance from the first, though few are aware of the great distances through which this influence is felt. As early as 1884 messages sent through insulated wires, buried in the streets of London, were read upon telephone circuits erected on poles eighty feet away on the housetops. At the time it was imagined that this must have been due to accidental connections or to any other cause than the true one, namely electromagnetic induction, or the

influence which one conductor conveying currents exercises on another parallel to it, when separated by a dielectric or by mere space.

In 1885 some experiments were made in England with the view of determining the distance through which such influences will act; and it was found that ordinary telegraph working currents produced disturbances 2,000 feet away, while effects on parallel lines of telegraph ten and one-quarter miles apart were perceptible. Distinct speech was carried on through a distance of one-quarter of a mile.

As in the case of telegraphy by means of the Hertz waves, two methods of using the induction currents have been brought out. They differ from each other merely in the arrangement of the wires used at the sending and receiving stations. In one of these, wires are arranged parallel to each other, and in the other they are placed in coils. As early as 1883 Professor A. E. Dölbear read a paper on electric communication in which he described a method employed by him for the transmission of signals over distances of from sixty to one hundred feet. About a year later communication was maintained between the Isle of Wight and Southampton during a temporary suspension of the cable. The instruments used were a telephone in one circuit, and in the other about twenty-five Leclanche cells and an interrupter. The sound could be distinctly heard, and so communication was kept up until the cable could be repaired and was again in working order. Of the two lines used in this case, one extended from the sea at one end of the island through the length of the same, and entered the sea again at the other end, while the line on the mainland ran from a point opposite one end of the island wire through Southampton to Portsmouth, where it again entered the sea. The distance between the terminals at one end was about a mile, and at the other about six miles.

This use of the principle of induction is the most obvious method of signaling by electricity without the use of wires. It underlies the present method of transmitting human speech by electricity as well as that of producing light and power. It is not necessary for our present purpose to enter into a careful study of the subject of electromagnetic induction. Its most ordinary

manipulations will serve our purpose. Suppose we have a coil of copper wire consisting of many turns, the ends of which are connected with a telephone. If we place a similar coil as shown in Fig. 1, the ends of which are connected with a battery, within a few feet of the first-mentioned coil and parallel to the latter, each time the current is made and broken in the first coil connected with it, a current is produced by induction in the neighboring cell, which is connected with a telephone. This mysterious effect called induction, which takes place through the air between the coils, and is only manifested for the instant during which the elec-

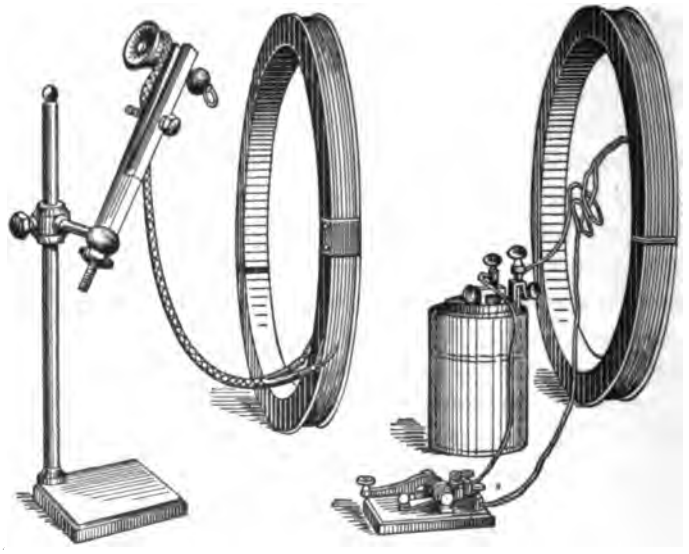

Fig. 1.

trical current is changing in the coil connected with the battery, — for it disappears when the electrical current becomes a steady flow and when the coils are stationary, and reappears the moment this current becomes fluctuating or when the coils are changing their position with respect to each other, — is supposed to be propagated through the ether in waves. Induction, therefore, can be looked upon as a transference of electrical energy from point to point.

In 1892 some elaborate experiments were made with the induction system of wireless telegraphy with the view of establishing

communication between the North Unst lighthouse, situated on Muckle Flugga at the north of Scotland, and the mainland. These experiments showed that the coil system gave the best results, but they were not of such a character as to be entirely acceptable to the lighthouse commission. The application of the coil system to communication with light vessels is to moor the vessel in the ordinary way, and lay out from the shore a cable, and circle the area over which the lightship moorings will permit her to travel by a coil of the cable the required diameter, which will be twice the length of her chain cable. On board the vessel there will be another coil of a number of turns of thick wire. A call arrangement and a telephone complete the outfit.

It will be readily understood that the distance over which such a system can be operated must necessarily be very limited, and that for transmission on a commercial scale, where the distance to be traversed is to be measured by miles instead of yards, it will be found to be wholly inadequate. In fact, it has long since been dropped from the possible number of competitors in the field, and can only be regarded as an interesting laboratory experiment, and yet it holds an important place in the developement of the practical wireless telegraph.

The true wireless telegraph owes its existence to what are known as the Hertz waves, which take their name from Professor Heinrich Hertz, of Bonn, though their existence was first indicated by Clerk Maxwell. During his investigations he promulgated the theory that light, heat, and electricity were combined, so that taken in connection with Faraday's researches and Clerk Maxwell's prophetic investigations, Hertz's experiments have definitely and conclusively proved the existence of one medium throughout all space, called ether, through which waves of energy, called radiations, are propagated with the same velocity, but in different forms and with different frequencies, although all of the same character. At one end of the scale we have actinic disturbances producing photographic impressions; at the other end of the scale electric waves producing electro-magnetic disturbances, while the intermediate radiations give light and heat. Actinic waves are extremely minute and number many millions per second, electric waves are very long and may number only hundreds per second. Like light

waves, they are promulgated in straight lines, they are subject to interference, and they may even be polarized.

If we take a conductor through which a rapidly alternating current is being supported by any means, it throws the ether which surrounds it into oscillations. Energy is thus radiated away in electric waves. The electric waves spread out in all directions, as do waves of light; and if they fall on similar conductors properly placed and sympathetically prepared, these waves of energy are transformed back again into alternating currents, which give evidence of their presence. This presence is indicated by a telephone if the frequency of the alternating currents is brought within the range of the ear. Hertz and his followers experimented with waves of much shorter length and with sparks in the air.

The prime source of energy in these experiments has been either a steam-engine or a galvanic battery. This has produced, by suitable machinery, rapidly intermittent or alternating currents, which have been transmitted through a primary circuit. At some distance away from this circuit there has been a secondary telephone circuit; and between these two circuits the only connecting medium has been the ether, which has been thrown into electric oscillation, and it has been across this space that signaling without wires has been carried on. In all cases in the early experiments, the primary circuits were of such frequency as to produce a musical note in the telephones fixed in the secondary circuit, which could easily be read if sent in the dots and dashes of the Morse code.

The action of these waves is summed up by Professor Oliver Lodge as follows: "Any conductor electrically charged or discharged with sufficient suddenness must emit electrical waves into the ether, because the charge given to it will not settle down instantly, but will surge to and fro several times first; and these surgings or electrical oscillations must, according to Maxwell, start waves in the ether, because at the end of each half swing they cause electrostatic, and at the middle of each half swing they cause electromagnetic effects; and the rapid alternation from one of these modes of energy to the other constitutes ethereal waves. If a wire is handy they will run along it, and may be felt a long way

off. If no wire exists they will spread out like sound from a bell, or light from a spark, and their intensity will decrease according to the inverse square of the distance.

"Maxwell and his followers well knew that there would be such waves, they knew the rate at which they would go, they knew that they would go slower in glass and water than in air, they knew that they would curl around sharp edges, that they would be partly absorbed but mainly reflected by conductors, that if turned back upon themselves they would produce the phenomena of stationary waves, or interference, or nodes and loops; it was known how to calculate the length of such waves, and even how to produce them of any required or predetermined wave length from many thousand miles to a foot. Other things were known about them which would take too long to enumerate; any homogeneous insulator would transmit them, would refract or concentrate them if it were of suitable shape, would reflect none of a particular mode of vibration at a certain angle, and so on, and so on.

"All this was known with varying degrees of confidence, but Hertz supplied the verification. He inserted suitable conductors in the path of such waves, — conductors adapted for the occurrence in them of induced electric oscillation; and to the surprise of every one, himself doubtless included, he found that the secondary electric surgings thus excited were strong enough to display themselves in minute electric sparks."

It will thus be seen that the electric waves that are now utilized for the purposes of wireless telegraphy have been rushing to and fro through space for all time without detection, and the principal thing to be done after their detection was to catch and harness them so that they could be made to perform useful work.

This catching was done by means of a very simple instrument that is known as a "coherer;" and this, too, was the result of long study and observation. It depends upon what was probably the first observed of all of the electric phenomena with which we are now familiar. It is well known that if a piece of amber, rubber, or sealing-wax is rubbed, it will possess the power of attracting small particles and causing them to cohere to itself. This has been known and observed for untold ages. In 1850, however,

Guitard made some observations, and found that, when dusty air was electrified, the particles of dust would tend to attach themselves together in the form of strings. Again, in 1879, it was observed that the drops of water of a small fountain, when exposed to the influence of an excited piece of sealing-wax, would not separate into small drops, but would cohere in large ones. It is probably due to the same principle that the drops of rain are so much larger in thunder-storms than in ordinary showers. The electric condition of the clouds causes the drops of water to cohere into large ones. These phenomena have been observed for many years, but it was not until 1890 that M. E. Branly of Paris made a practical application of the principle in the form of a radio-conductor, or coherer as it is ordinarily known.

He, in common with others, knew of the enormous resistance that is offered to the passage of the electric current by metals in a powdered condition. In the course of his experiments, he found that by placing some of this powder in a glass vial with two cylindrical copper tubes pressing against it, and connected in a circuit, that the powder acted as a complete insulator, and prevented the passage of the current. If, however, this apparatus was exposed to the shock caused by an electric spark, the particles would instantly cohere, and their resistance would be reduced to an insignificant amount. This condition would continue until something was done to decohere the particles, when the original resistance would be at once set up. This, then, is the sensitive receiver that is used in wireless telegraphy. It is connected with a wire so placed that it can receive the Hertz waves that are sent out from the transmitting station. These waves so affect the coherer that it permits of the passage of the local current, which is again cut off by gently tapping the glass containing the powdered metal.

It will at once be realized, from the foregoing, that the apparatus of wireless telegraphy may be very simple, as indeed it is; but like many other simple things it has required great patience and more perseverance to bring it to the condition approaching perfection that it now seems to have a prospect of reaching.

That system of wireless telegraphy which is best known is the one that is associated with the name of Signor Guglielmo

Marconi Transatlantic Station at South Wellfleet, Cape Cod, Mass. Tower 210 ft. high.

From this Station was sent the first wireless message of President Roosevelt to King Edward VII., January, 1903.

Marconi. The apparatus employed consists of a transmitter and receiver.

When long distances are to be bridged, and it is not necessary that the signals should be sent in one definite direction, a transmitter is used similar to that shown in Fig. 2. There are two small spheres connected to the terminals of the secondary winding of an induction coil *c*. One of these is also connected to a wire running to the earth, while the other is connected to a vertical conductor *W*, which is called the aerial conductor. This transmitter works as follows: When the key *b* is pressed, the current of the battery *a* is allowed to actuate the spark coil *c*, which charges the oscillator or vertical wire *W*, and discharges through the spark gap between the two spheres. The discharge is an oscillating one,

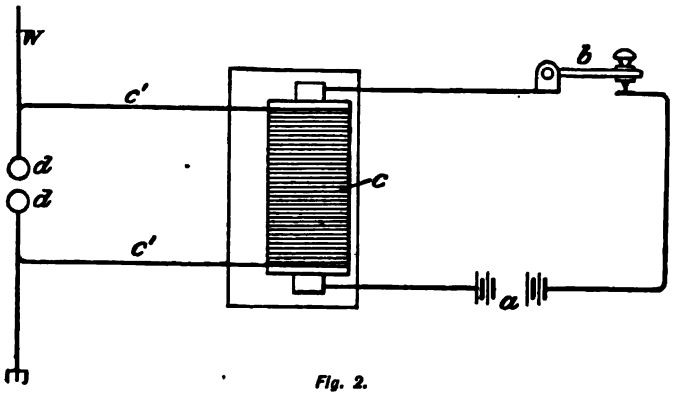

Fig. 2.

and the system of spheres and insulated vertical wire becomes a radiator of electric waves. It is easy to understand how, by pressing the key for long or short intervals, it is possible to emit a long or short succession of waves, which, when they influence the receiver, reproduce on it a long or short effect, according to their duration, in this way reproducing the Morse code or other signals transmitted from the sending station.

The receiving instrument is shown in Fig. 3, and has for one of its parts the sensitive tube, coherer, or radio-conductor, as it is variously called. The coherer used by Marconi consists of a small glass tube about two inches long, into which two metal pole pieces, Fig. 4, are tightly fitted. They are separated from each other by a small gap, which is partly filled with a mixture of nickel and

silver filings. This coherer forms part of a circuit containing the local and sensitive telegraph relay actuating another circuit, which circuit works a trembler, *p*, or decoherer and recording instrument, *h*. In its normal condition the resistance of the filings uninfluenced in *j*, is infinite, or at least very great, but when

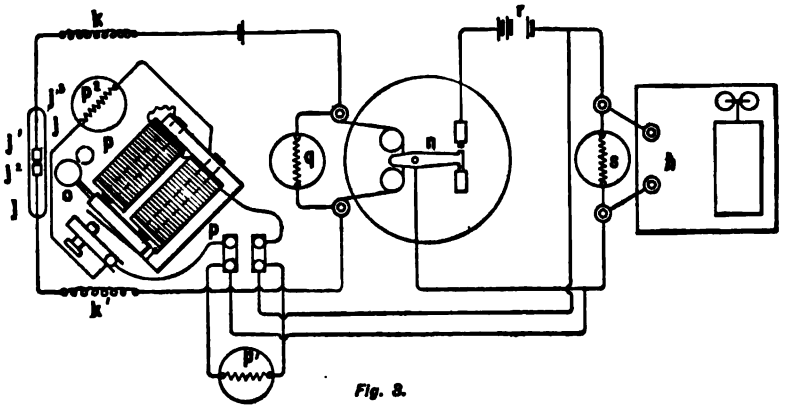

Fig. 8.

the filings are influenced by electric waves or surgings, cohesion instantly takes place, and the tube becomes a comparatively good conductor, its resistance falling to between 100 and 500 ohms. This allows the current from the local cell to actuate the relay, *n*. One end of the tube is connected to the earth, and the other to a vertical conductor similar to that of the transmitter, Fig. 2; or, if reflectors are used, a short strip of copper is connected to each end, as shown in Fig. 6. The lengths of these strips of copper must be carefully determined, as good results cannot be obtained unless they happen to be of the proper length, which will cause them to be in tune or syntony with the transmitted oscillation. All of the electromagnetic apparatus in the receiver is shunted by non-inductive resistances in such manner that there may be no sparking at the contacts, and no sudden perturbations or jerks caused by the local battery current near the coherer. The relay tapper and telegraph instrument, if not properly shunted, produce disturbing effects, the result of which is to prevent the coherer from regaining its sensitive condition after the receipt of electrical oscillations. Small choking coils, $k\,k^1$, are introduced between the coherer and the relay. They compel the oscillating current

due to the electric waves to traverse the coherer rather than waste its energy in the alternative path offered by the relay. The oscillations, induced on the strips *k k* (or the aerial conductor *W*, which acts as a resonator) by the radiation from the oscillator, affect the sensitive tube. This effect on the tube consists, as we have said, in a great increase of its conductivity, thus completing the circuit, and allowing the current from the cell to actuate the relay. The relay, in its turn, causes the larger battery, *r*, to pass a current through the tapper or interrupter, *p*, and also through the electromagnets of the recording instrument, *h*.

The tapper or trembler is so adjusted, as to tap the tube and shake the filings in it. If, in the instant during which these various actions take place, the electrical oscillations had died out in the resonator, the shake or tap given to the tube by the hammer, *o*, would have restored it to its normal high resistance condition, and the Morse instrument or recorder would have marked a dot on the tape; but if the oscillations continue at very brief intervals the acquired conductivity of the tube, *j*, is destroyed only for an instant by the tap of the trembler, and is immediately re-established by electrical surgings; and therefore the relay tapper and telegraph instrument are again actuated, and so on until the oscillations from the radiator have ceased. The practical result is, that the receiver is actuated for a time equal to that during which the key is pressed at the transmitting station. For each signal, however short, the armatures of the relay and tapper perform some very rapid vibrations dependent on each other. For it is the action of the relay which starts the tapper, but the tapper by its motion interrupts the relay. The armature of the Morse recording instrument being rather heavy, and possessing a comparatively large inertia, cannot follow the very rapid vibrations of the tongue of the relay, but remains down all of the time during which the rapidly intermittent action of the receiver lasts. In this way the armature of the inker gives a practically exact reproduction of the movements of the key at the transmitting end, dashes coming out as dashes, and dots as dots.

A great deal of importance is placed on the height of the vertical wire *W*. It is upon this height that the distance over which the signals can be transmitted depends. Experiments have

shown that a height of about 114 feet is sufficient for the transmission for 82 miles. Taking this as a datum line, it has been found, also, that the distances vary as the square of the heights.

This practically constitutes the whole of the transmitting and receiving stations for wireless telegraphy. The relays, batteries, and other detail parts of the apparatus differ only in detail from that in common and current practice in all telegraph offices, with the exception that the instruments used in wireless telegraphy are more delicately adjusted. The one part which has no counterpart in the common telegraph is the coherer, whose construction has already been explained. This portion of the apparatus is shown in Fig. 4, on an enlarged scale. It consists of a small glass tube about one-tenth inch in internal diameter and about two inches long. Two silver pole pieces are lightly fitted into this tube, separated by a gap of about .04 inch, containing a mixture of 96 parts of nickel and 4 parts of silver, not too finely granulated, and worked up with the merest trace of mercury. This powder must not be packed too tightly or the action will be irregular and oversensitive to slight outside disturbances, while if too loose it will not be sufficiently sensitive. It is found that the best adjustment is obtained when the coherer works well under the action of the sparks of a small electric trembler placed at a distance of a little more than three feet. The tube is then exhausted on a mercury pump until the pressure falls to about .04 inch, when the tubulure left for the exhausting is sealed off. The tubes are tested over a distance of 18 miles before being put into service; and when all of the requisite precautions are observed, they are as reliable as any other telegraphic instrument, and no more likely to get out of order.

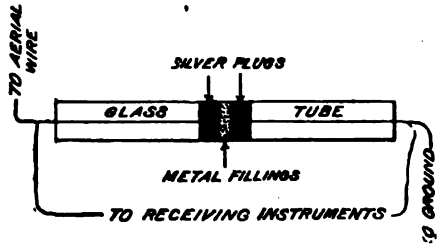

Fig. 4.

Attention has already been called to the fact that the Hertz waves resemble those of light and heat in that they can be reflected, refracted, and absorbed. With the plain vertical wire rising as described above, it is evident that the waves are transmitted in all directions. In order to prevent this, and send them

in one direction only, it is necessary that some sort of a reflector should be used. It has been found that the metals or conductors can be used as reflectors, while the non-conductors permit the waves to pass through them without hindrance. By means of

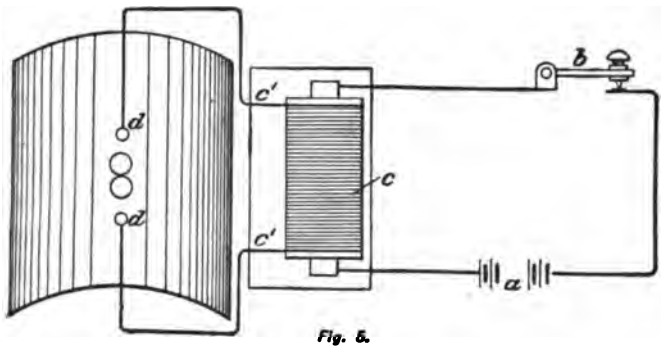

Fig. 5.

reflectors attached to the apparatus, as shown in Fig. 5, it is possible to project the rays in one almost parallel beam which will not affect any receiver placed out of its line of propagation,

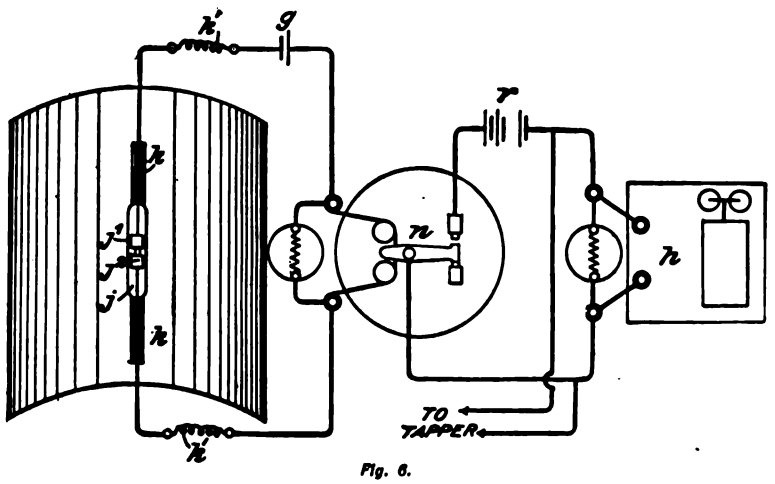

Fig. 6.

whether the said receiver is or is not in tune or syntony with the oscillations transmitted. Fig. 6 shows a similar reflector attached to a receiving apparatus.

Having once perfected the apparatus so that the messages could be sent through space, a difficulty arose that seemed for a

time to threaten to make the whole system useless, in that any receiver could be made to receive the messages sent from any transmitter. Add to this the fact that all receivers were more or less sensitive to all of the Hertz waves in their neighborhood, it is at once evident that, where a number of transmitters were at work, and affecting the ether, any receiver in the affected region would be picking up signals from any and all of these transmitters, with the result that no distinct message would be received from any one of them, and nothing but chaos would prevail. Again, in case the ether was not so disturbed as to cause a multiplicity of disconnected signals to be received, there was the great objection to the system on the ground that messages could be picked up and read by outside parties, and there could be no possible privacy. Such a state of affairs would condemn the method, especially if it were to be offered for military purposes.

In order to overcome this difficulty, a tuning of the oscillations of the transmitter has been resorted to. The receiving instrument is now so adjusted or tuned, that it will only receive syntonic oscillations, with the result that, though the ether may be filled with a most complex variety of oscillations coming from a great number of transmitters, each receiver picks out those

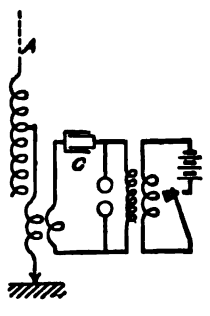

Fig. 7.

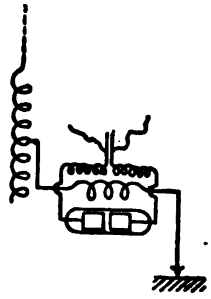

Fig. 8.

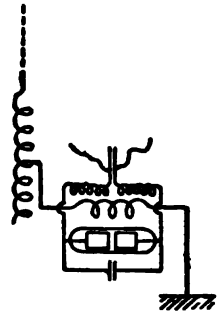

Fig. 9.

vibrations which are intended for it, and, converting them into messages according to the Morse code, is unaffected by any and all other oscillations with which it is not in tune.

The syntonized transmitter is shown in Fig. 7. The period of oscillation of the vertical conductor A can be increased by introducing turns, or decreased by diminishing their number, or

by introducing a condenser in the series with it. The condenser *C*, in the primary circuit, is constructed in such a manner as to render it possible to vary its electrical capacity. The receiving station arrangements are shown in Figs. 8 and 9.

Here we have a vertical conductor connected to the earth through the primary of the transformer, the secondary circuit of which is joined to the coherer or detector. In order to make the tuning more marked, an adjustable condenser is placed across the coherer, as shown in Fig. 9.

It will be quite impossible within the limits of this article to take up all of the electrical phenomena that have to do with the latest developments of syntonic wireless telegraphy; but it will suffice to say that the troubles that were in prospect after the first successfully transmitted messages, have entirely disappeared, and it is now possible to send messages with all the secrecy that attend that of the ordinary telegraph, and indeed a great deal more so, in that the common wires can be tapped by any one having access to them, while the syntonic message cannot be waylaid by any coherer not in tune with the original oscillations.

In this connection a few words may be added regarding the present improved arrangements at the stations for sending and receiving messages. The original elevated straight wire, which was used as a transmitter, was a very good radiator of electrical waves; but its electrical oscillations died away with great rapidity, although they were very powerful while they lasted. The result was that it would affect receivers or resonators of considerably different pitch or period. The violence of its effect set them in action by one or two impulses, although those impulses did not correspond with their natural periods. If a radiator be used giving off much less energy at each vibration, but emitting a series of waves over an extended period, then it will only affect a resonator tuned to that particular frequency. It will take some time (measured in thousandths of a second) for the radiator to set up a swinging electro-motive force in the receiver sufficient to break down the insulation of the coherer, and to cause a signal to be recorded.

Early in 1900 the vertical wire was replaced by the arrangement shown in Fig. 10. In it the radiating and resonating

conductors take the form of a cylinder; a cylindrical earthed conductor being placed inside. This form of radiating and receiving area is very efficient, as compared with anything preceding it. One necessary condition of this system is that the inductance of the two conductors shall be unequal, it being preferable that a large inductance shall be joined to the non-earthed conductor. By using cylinders of zinc, only twenty-three feet high and five feet in diameter, good signals could be sent over thirty miles; and these were distinctly received, although other signals were passing. The closely adjacent plates and the large capacity of the receiver cause it to be a resonator possessing a very decided period of its own, and so no longer apt to respond to frequencies which differ from its own particular period. The receiver is not shown in Fig. 10, but consists of similar cylinders, the receiving induction coil, or oscillation transformer, being placed where the spark gap is in the old apparatus.

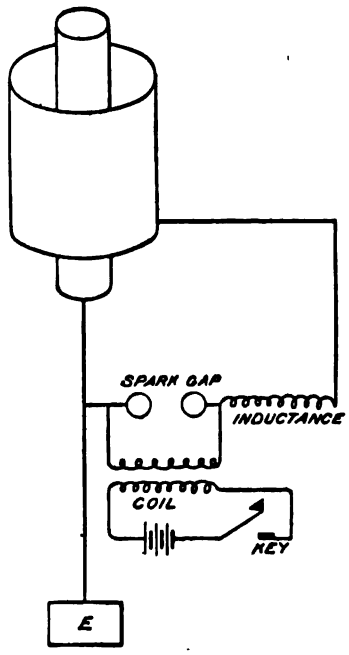

Fig. 10.

Reverting now to the transmitting apparatus in its simple form, Fig. 11 shows it somewhat more in detail than the illustrations heretofore presented. Two spheres of solid brass, A and B, are fixed in an oil-tight case of insulating material, so that a hemisphere of each is exposed, the other hemisphere being immersed in a bath of vaseline oil. The use of the oil has several advantages. It maintains the surfaces of the spheres electrically clean, avoiding the frequent polishing that was required by the original balls used by Hertz. It impresses on the waves excited by these spheres a uniform and constant form. It tends to reduce the wave lengths; for with this apparatus, which was designed by Righi, the waves are measured in inches, whereas those of Hertz were measured in yards. For these reasons the distance at which

effects are produced is increased. Two small spheres, *a* and *b*, are fixed close to the large sphere, and connected each to one of the secondary circuits of the induction coil, C, the primary circuit of which is excited by a battery, E, thrown in and out of action by the Morse key, K. Now, whenever the key is depressed, sparks pass; and since the system, A, B, contains capacity and electrical inertia, oscillations are set up in it of extreme rapidity. The line of propagation is out at the wire D, to the wire of the receiving station *d*, where the connection is made with the coherer as shown.

During the time when it was impossible to tune the transmitting and receiving instruments so that there could be a selection of messages, and everything that was sent was public property, so to speak, there was considerable activity along the lines already indicated in which the influence of ultra-violet light upon the sparking was brought to the front.

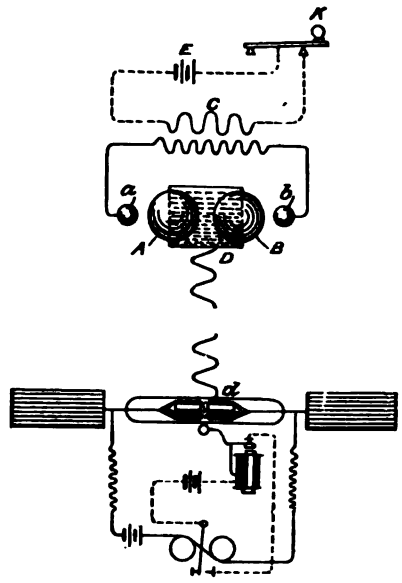

Fig. 11.

Among the systems worked out on this principle is that of Professor Zickler of Brunn. It is based upon the property possessed by luminous rays of short wave length (particularly the ultra-violet ones) of favoring or causing electric discharges. If, for example, we separate the poles of a Ruhmkorff coil in action until the difference of potential is no longer sufficient to cause a spark to continue to be produced between them, and the ultra-violet rays chance to strike these poles, the spark will be immediately re-established. Professor Zickler put this phenomenon to profit in the following manner: From the transmitting station he sends the ultra-violet rays of an electric arc in the direction of the receiving station. At the last named station these rays cause the formation of sparks, which produce electric waves that

act upon a coherer in such a way as to actuate a Morse apparatus.

As in the Marconi system, the spark here plays the chief rôle; but, instead of being produced at the transmitting station, it bursts forth and produces its effect at the receiving station.

At the transmitting station there is the means of establishing the beam of light, and it is projected through a quartz lens. It is necessary that the lens should be of quartz, so that the ultra-violet rays shall not be intercepted. In front of the aperture there is a screen of ordinary glass, which is actuated automatically after the manner of the shutter of a photographic camera.

As soon as the arc is established, the luminous pencil is projected through the aperture. Its brilliancy is in no wise altered by the glass screen, since the latter allows the visible rays to pass; but, inasmuch as ordinary glass absorbs the ultra-violet rays, no electro-luminous effect can be produced at the receiving station. These rays can only pass when the glass screen exposes the aperture, and it is then that the action intervenes at the other station. When the screen is opened and closed at proper intervals, there pass ultra-violet rays that correspond to the dots and dashes of the Morse alphabet. During the operation the ultra-violet rays are the only ones shut off, the visible rays passing without interruption.

An observer of the luminous pencil can, therefore, read no signal, since the pencil undergoes no alteration that is capable of being perceived by the eye.

In order to put himself in a position for obtaining signals, the person at the receiving station must first so place himself that the axis of his apparatus shall coincide with that of the luminous pencil of the correspondent whom he faces. He afterwards actuates the induction coil, and regulates his rheostat until the tension has reached the normal point; that is to say, the exact limit at which the sparks cease to pass between the electrodes. This being done, as soon as the correspondent displaces the glass screen of his transmitting apparatus, the ultra-violet rays will pass and strike the electrodes of the receiving apparatus, and a spark will make its appearance between them. As soon as these rays are interrupted again the spark will disappear.

Fig. 12. NANTUCKET WIRELESS TELEGRAPH STATION.

It is evident that such an apparatus is somewhat limited as to the distance over which it can be made to operate; and indeed, as a matter of fact, its work has been restricted to but little more than a mile.

There are other means of wireless telegraphy that have been brought out from time to time, notably those in which attempts have been made to send messages to a moving railway train. Such attempts have met with more or less success, and have usually been based on the generation of induction currents. Had there been any great demand for such a method of signaling, it would probably have been developed to a high degree of efficiency; but the amount of business that it is desired to transact in this particular direction is so limited that there has been little or no inducement to perfect the apparatus. In fact, in one instance where it was applied to a train and operated successfully for several months, it was finally abandoned, simply for the reason that the amount of work offered would not pay for the maintenance of an operator on the cars.

As for the applicability of the wireless telegraph as it is now understood, and as it has been especially developed by Marconi, there are many places where nothing else that is known can take its place. The most evident place of this sort is the signaling between ships at sea. The wireless telegraph is not impeded in its action by fog or wind, and by the use of suitable reflectors it is quite possible to determine the exact direction of an invisible vessel. It has also been applied to the signaling of ships on their approach to a harbor, and the news of the time of their probable arrival is now sent on in advance twenty-four hours before they are sighted. Such a shore station is illustrated in Fig. 12, which represents the one on Nantucket Island for the signaling to ships sailing from and bound to New York. In external appearance it emphasizes the simplicity of the arrangements of the system as set forth in the preceding pages. It consists merely of a tall mast, suitably guyed, and fitted with certain wires whose arrangement is totally devoid of complication. Communication between the shore and lightships, that has heretofore been almost impossible on account of the difficulty of maintaining connections, now becomes a matter of comparative ease, and

outlying vessels can send signals to the shore in case of any emergency. It has been thought that much of the cable work will be superseded by messages over the wireless circuit, and that many of the former will be rendered useless. Such a state of affairs can hardly be expected, however, since it is not in accordance with past experience. It was supposed that the telephone would take away, and possibly destroy, the business of the regular telegraph companies, and probably a great deal of work that would otherwise be sent as telegrams, now goes by telephone; but the convenience of the latter has built up a distinct realm of its own, and the original lines, instead of being injured by what was once thought would be a destructive competition, do not feel it at all.

It is unsafe to make predictions as to what will be the future outcome of this new and wonderful method of communication, for it is still only in its infancy, but it may safely be expected to fulfill, and more than fulfill, all reasonable expectations.

As the physicist knows that there are but few really fundamental principles in mechanics, so it seems that in the domain of the more abstruse departments there is an apparent tendency towards unifications. We know that the underlying principles of light, heat and electricity are one and the same; and wireless telegraphy, as now practiced, is the most recent and interesting exponent of the fact.

APPENDIX

QUESTIONS IN REVIEW

The following lists of questions afford the reader a means of testing his knowledge of the subjects treated in the present volume. Any one who has carefully read the foregoing subjects should be able to answer every question accurately. The reader is advised to go through the questions thoroughly, working out his answers and checking his results with the answers given. This will afford a valuable means of fixing the matter in mind. Students who are preparing for examinations for college, civil service or engineer's license will find the questions of the greatest value.

REVIEW QUESTIONS

ON THE SUBJECT OF

ELEMENTS OF ELECTRICITY.

1. What is a magnetic substance?
2. Name the essential elements of a voltaic cell.
3. Upon what does the capacity of a condenser depend?
4. If it were desired to reduce the magnetism in a piece of steel, how could this be accomplished?
5. What is a loadstone?
6. What is the effect of self-induction upon the current?
7. How may the internal resistance of a cell be made of small amount?
8. Why does the compass needle point approximately north and south?
9. What is an electro-magnet?
10. Describe the process of electrotyping.
11. If one end only of a glass rod is rubbed with silk, will or will not the unrubbed end be charged by electricity, and why?
12. How may it be shown that the poles of a magnet are dissimilar?
13. Name a few applications of the heating effects of currents.
14. What is the source of electricity in the voltaic cell?
15. How may it be proved that the charges produced by frictional contact, although different in kind are equal in amount?
16. Give a definition of an accumulator.
17. What substance is the best conductor of electricity, and what one is the best insulator?
18. Suppose a piece of ivory and a piece of sulphur to be rubbed with silk. After a suspended pith ball has been touched

by the sulphur, will it be attracted or repelled by the ivory, and why?

19. What is an electroscope?

20. Explain how polarization is overcome in double fluid cells.

21. How may it be shown that the field of a magnet exerts its influence in certain definite directions?

22. What are the essential parts of a condenser?

23. How may it be shown that the charge upon a body resides upon its surface?

24. What is meant by the terms "primary coil" and "secondary coil"?

25. How does the method of "forming" the plates of a Planté cell differ from that of "forming" plates of the Faure type?

26. Why does attraction take place between a charged body and a conductor brought within its inductive influence?

27. In what manner does polarization decrease the power of a cell?

28. State three ways in which a current may be induced in a coil of wire.

29. What is meant by electrolysis? What is an electrolyte? An anode? A kathode?

30. Upon what main factors does the amount of charge induced by a charged body upon a conducting body depend?

31. State Joule's law.

32. How may it be shown that a wire carrying a current is surrounded by a magnetic field?

33. (*a*) When glass is rubbed by wool, which substance receives a positive charge, and which one a negative charge? (*b*) Does the charge produced on the glass exceed in quantity that produced on the wool?

34. Why is it possible to obtain very high electromotive forces by means of the induction coil?

35. Explain why there is no gain in energy by use of the electrophorus without a corresponding expenditure of work.

REVIEW QUESTIONS

ON THE SUBJECT OF

THE ELECTRIC CURRENT.

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1. (*a*) Explain what is meant by electromotive force. (*b*) What is its unit of measurement, and by what value is it represented?

2. (*a*) What is necessary to cause an electric current to flow? (*b*) What is meant by the strength of a current? (*c*) What is its unit of measurement, and by what value is it represented?

3. What is the unit of resistance and by what value is it represented?

4. Upon what three general factors does resistance depend?

5. What length of copper wire 2 millimeters in diameter will have the same resistance as 12 yards, 1 millimeter in diameter? Ans. 48 yards.

6. State Ohm's law.

7. Two wires, whose resistances are respectively 28 and 24 ohms, are placed in parallel in a circuit so that the current divides, part passing through each. What resistance is offered by them to the current? Ans. 12.92 + ohms.

8. Fifty Grove's cells (E. M. F. = 1.8 volts) are in series, and united by a wire of 15 ohms resistance. If the internal resistance of each cell is .3 ohm, what is the current? Ans. 3 amperes.

9. (*a*) What is the unit of quantity of electricity? (*b*) Define the ampere-hour.

10. What is the power in watts when 4000 joules of work are done in 50 minutes? Ans. 1.33 + watts.

11. How many horse-power are equivalent to 83 kilowatts? Ans. 111 + horse-power.

12. What is a shunt circuit?

13. A current of 18 amperes flows in a circuit whose resistance is 116 ohms. What is the voltage? Ans. 2088 volts.

14. The resistance of 312 feet of a certain wire is 2.08 ohms. What would be the resistance of 240 feet of the same wire? Ans. 1.6 ohms.

15. A total current of 56 amperes passes through a divided circuit having the resistance of its branches equal to 28 and 4 ohms respectively. What is the current in each branch?

Ans. In the 28-ohm branch, 7 amperes.
In the 4-ohm branch, 49 amperes.

16. What is the value of the current when 4 ampere-hours are delivered in a circuit in 20 minutes? Ans. 12 amperes.

17. (*a*) Define the joule. (*b*) Define the watt.

18. A 220-volt circuit supplies a current of 18 amperes. What is the power in kilowatts? Ans. 3.96 K. W.

19. If the resistance of a certain wire is 2.3 ohms per 1000 feet, how many feet of the wire will be required to make up a resistance of 17.8 ohms? Ans. 7739 + feet.

20. What is the resistance of a wire having a diameter of .2 inch if the resistance of the same length of similar wire having a diameter of .04 inch is 64.2 ohms? Ans. 2.56 + ohms.

21. Define specific resistance.

22. The resistance of a circuit is 1.8 ohms and the voltage is 110. What is the current? Ans. 61 + amperes.

23. A circuit contains a voltaic cell generating an electromotive force of 1 volt. Its electrodes are connected by three wires in parallel of 2, 3, and 4 ohms resistance respectively. The resistance of the cell is $\frac{1}{18}$ ohm. What is the current?

Ans. 1 ampere.

24. Eight cells each having an E. M. F. of .9 volt and an internal resistance of .6 ohm are connected in parallel, and the external resistance is 3.4 ohms. Find the current.

Ans. .26 ampere (approx.).

25. What quantity of electricity will be conveyed by a current of 40 amperes in half an hour? Ans. 72,000 coulombs.

26. The resistance of a circuit is 10 ohms, and the current is 33 amperes. What is the power in watts? Ans. 10,890 watts.

27. How many watts are equivalent to 14 horse-power?
Ans. 10,444 watts.

28. Five conductors having resistances respectively equal to 14, 3, 20, 31 and 8 ohms are joined in series, and the E. M. F. applied to the circuit is 50 volts. What is the current?
Ans. .65 amperes.

29. (*a*) Define conductance. (*b*) Define conductivity.

30. What is the resistance of 10 feet of annealed gold wire .001 inch in diameter at 32° F., if the resistance of an inch cube of the substance at 32° F. is .8079 microhm? Ans. 123 + ohms.

31. A copper wire has a resistance of 13.5 ohms at 43° F. What is its resistance at 57° F? Ans. 13.91 + or nearly 14 ohms.

32. What must be the resistance of a 220-volt circuit if the current is to be 70 amperes? Ans. 3.14 + ohms.

33. The E. M. F. applied to a circuit is 582, and the current is 8 amperes. A number of lamps connected in the circuit require a total drop of 522 volts. Find the resistance of the remaining portion of the circuit. Ans. 7.5 ohms.

34. A circuit is made up of six wires connected in parallel and having resistances of 72, 60, 21, 36, 40 and 210 ohms respectively. Find their joint resistance. Ans. 7.3 + ohms.

35. When a cell, which has an internal resistance of 1.39 ohms and an E. M. F. on open circuit of 1.32 volts, is supplying a current of .29 ampere, what is its available E. M. F.?
Ans. .92 volts (approx.).

36. With a current of 20 amperes how much time will be required to deliver 4,000 coulombs. Ans. 3 minutes, 20 seconds.

37. The voltage of a circuit is 103 and the current is .5 ampere. What energy is expended in a minute and a half?
Ans. 4635 joules.

38. The resistance of a coil of platinoid wire at 98° C. is 3014 ohms. What resistance would the coil have at 18° C.?
Ans. 2962 ohms (approx.).

39. What is the resistance of 28 feet of No. 6 (B. & S.) pure copper wire at 90° F.? Ans. .0118 + ohm.

40. If a resistance of 116 ohms be inserted in a circuit, and it is desired to maintain a constant current of 9.6 amperes, how much must the voltage of the circuit be increased?
Ans. 1113 + volts.

41. When a current of 14 amperes flows in a circuit whose resistance is 54 ohms, what energy in kilowatt-hours is expended in half an hour? Ans. 5.292 kilowatt-hours.

42. Explain the difference between the kilowatt and the kilowatt-hour.

43. What number of calories will be developed by a current of .14 ampere flowing through a wire of 4 ohms resistance for 5 minutes? Ans. 5.6 + calories.

44. The voltage applied to a circuit in which three wires are connected in parallel is 107. Find the current in each branch if the separate resistances are respectively 43, 9 and 25 ohms.

Ans. In 43-ohm branch, 2.4 + amperes.
In 9-ohm branch, 11 + amperes.
In 25-ohm branch, 4.2 + amperes.

45. How many horse-power are equivalent to 1048 watts?

Ans. 1.4 + horse-power.

46. If the resistance of 1 foot of annealed silver wire .001 inch in diameter at 32° F. is approximately 9.02 ohms, what is the resistance of 4 miles of the wire .01 inch in diameter at a temperature of 90° F.? Ans. 2137 + ohms.

47. Twenty large Leclanche cells (E. M. F. = 1.5 volts, resistance = 0.5 ohm each) are in a circuit in which the external resistance is 10 ohms. Find the strength of current which flows (*a*) when the cells are joined in series; (*b*) when all the cells are in parallel; (*c*) when there are 2 files each having 10 cells in series; and (*d*) when there are 4 files each having 5 cells in series.

Ans. Amperes (*a*) 1.5; (*b*) 0.149; (*c*) 1.2; (*d*) 0.706.

48. How many kilowatts are equivalent to 150 horse-power?

Ans. 111.9 K. W.

49. If a current of 9.3 amperes flows when the voltage of a circuit is 110, how much resistance must be inserted in the circuit to reduce the current to 3.4 amperes? Ans. 20 + ohms (approx.).

50. A current of 26 amperes is flowing in a circuit which has a voltage of 500. What is the equivalent power in mechanical units? Ans. 17.4 + horse-power.

REVIEW QUESTIONS

ON THE SUBJECT OF

THEORY OF DYNAMO-ELECTRIC MACHINERY.

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1. State the distinction between a generator and a motor.

2. (*a*) What is the object of the commutator? (*b*) Of what does it consist?

3. Why is it necessary to laminate the core of an armature?

4. How is the number of ampere-turns of a coil carrying current obtained?

5. What different parts make up the magnetic circuit of a dynamo?

6. What is meant by the density of a magnetic field?

7. Suppose a conductor and magnetic field both to be horizontal and at right angles to each other, the direction of the field being away from the observer; if the conductor were moved upward across the field, would the direction of the current induced in the conductor be from left to right or from right to left?

8. What is meant by the building up of a machine?

9. State briefly what is meant by hysteresis.

10. What do the electrical and stray power losses of a dynamo include?

11. (*a*) What is the relation between the direction of a current in a conductor and the direction of its magnetic field? (*b*) Between the polarity of an electro-magnet and direction of current in its coil?

12. Of what does the armature consist?

13. How are the coils of an armature successively short-circuited when a machine is in operation?

14. Upon what three factors does the electro-motive force generated by a conductor moving in a magnetic field depend?

15. In calculating the voltage of a machine what several factors must be considered?

16. What disadvantages has the magneto-dynamo?

17. When a closed coil is moved in a magnetic field in such a manner that there is no change in the number of lines passing through it, why will no current flow?

18. How are the coils connected to the commutator bars in a ring winding?

19. What opposes the free rotation of the armature when a dynamo is under load?

20. Describe briefly how the magnetization of an iron core increases as the ampere-turns of a coil are increased.

21. When is a coil said to be in the neutral position?

22. (a) Why does a single coil rotating between the poles of a magnet give a pulsating current? (b) State briefly how the pulsating current in the coils of a dynamo is made to give a current of uniform strength in the external circuit.

23. (a) Describe the difference between closed coil and open coil windings. (b) Between ring and drum windings.

24. Why is it that brushes of drum-wound machines are placed opposite the poles instead of between them as in ring-wound machines?

25. State the different causes which distort the field of a dynamo.

26. Why is it necessary to shift the position of the brushes when the load on a dynamo changes?

27. In the drum winding why is it necessary to have the forward and return portions of a coil under poles of opposite polarity?

28. What are the disadvantages of the series dynamo?

29. State the difference in construction between a series and shunt dynamo.

30. Describe the field connections of a compound-wound machine.

31. What E. M. F. will be generated when a conductor 48 centimeters long cuts across a uniform field of 3,600 lines per square centimeter at the rate of 50 meters per minute?

Ans. .144 volt.

32. At what rate of speed must a conductor 90 centimeters long move in order to generate .8 volt, the strength of the field being 6,500 lines per square centimeter?

Ans. 136.7 cm. per second.

33. What will be the voltage of a bipolar machine which has 650 surface conductors 20 centimeters long, 75 per cent of which are opposite the pole pieces, when the armature is run at 900 revolutions per minute? The diameter of the armature is 25 centimeters and the field density at the poles is 4,000.

Ans. 229+ volts.

34. A bipolar machine has an armature 50 centimeters in diameter with 750 surface conductors 30 centimeters long. Of the total number of conductors 70 per cent are opposite the pole pieces and the field density is 5,000 lines per square centimeter. What must be the speed of the armature to generate a voltage of 220?

Ans. 213+ revolutions per minute.

35. In a four-pole machine the armature carries 800 surface conductors each 60 centimeters long, the diameter of the armature being 80 centimeters. The field density at the poles is 4,500 lines per square centimeter, and the percentage of conductors opposite the pole pieces is 80. What will be the voltage of the machine when running at 500 revolutions per minute?

Ans. 904+ volts.

36. What are the electrical losses in a series dynamo which delivers 20 amperes, the armature resistance being .4 ohm, and that of the series winding being .2 ohm?

Ans. 240 watts.

37. A 220-volt compound machine is to deliver 200 amperes. The resistances of the armature, series and shunt windings are .02, .003 and 120 ohms respectively. What are the electrical losses?

Ans. 1,323.3+.

REVIEW QUESTIONS

ON THE SUBJECT OF

DIRECT CURRENT DYNAMOS.

1. Explain briefly the two different methods of distributing electrical power.

2. (*a*) Why does the series characteristic curve bend over and the voltage begin to decrease when the current is large? (*b*) Explain why the E. M. F. of a series dynamo decreases very rapidly from about two-thirds its maximum value upon decreasing the current. (*c*) Draw a diagram of the circuit of a series dynamo.

3. (*a*) Why is the voltage of a shunt dynamo at its maximum an open circuit? (*b*) Why does the voltage of a shunt dynamo decrease when the load is increased? (*c*) Draw a diagram of the circuit of a shunt dynamo.

4. (*a*) What is the general form of the characteristic of a compound dynamo? (*b*) What is the difference between a long shunt compound-wound dynamo and a short shunt compound-wound dynamo? (*c*) Draw a diagram of the circuit of a short shunt compound machine.

5. What values of E. M. F. and current are used in plotting the external, internal and total characteristics of the shunt dynamo?

6. How does the construction of shunt coils differ from that of series coils?

7. (*a*) Why does sparking occur if the position of the brushes is such that the short-circuited coils generate no E. M. F.? (*b*) What is the correct position of the brushes for sparkless running?

8. Why should not the current pass through the springs which are used to give the brushes proper pressure upon the commutator?

REVIEW QUESTIONS

ON THE SUBJECT OF

DIRECT CURRENT MOTORS.

1. State briefly the fundamental principle of a motor.

2. Upon what does the speed of a motor depend?

3. The armature resistance of a motor is .6 ohm and the E. M. F. applied at the brushes is 120 volts. When the counter E. M. F. is 82 volts, what current passes in the armature?

Ans. 63.+ amperes.

4. Explain why the speed of a series motor on a constant potential circuit increases when the load is removed.

5. What are the different ways of reversing the direction of rotation of motors?

6. If the output of a motor is 60 horse-power and the armature makes 490 revolutions per minute, what is the torque?

Ans. 643.+ foot-pounds.

7. Why is it necessary to cut out the starting resistance of a motor in order that it may be brought up to speed?

8. In what direction will the armature of a shunt generator rotate when run as a motor compared with the direction of rotation when run as a generator? Explain.

9. Explain briefly the different methods used to vary the speed of shunt motors.

10. A shunt motor on a 230 volt circuit takes 55 amperes at full load, the speed being 760 revolutions per minute. What resistance is it necessary to insert in the armature circuit in order to have the motor run at $\frac{3}{4}$ speed when the torque is $\frac{1}{2}$ that at full load?

Ans. 2.8 ohms (approx.).

11. In stopping a shunt motor why should the main switch be opened *before* the armature circuit is broken?

12. What are the advantages and disadvantages of series motors?

13. The current in the armature of a shunt motor is 30 amperes and the E. M. F. at the brushes is 220 volts. If the armature resistance is .8 ohm, what is the counter E. M. F.? Ans. 196 volts.

14. What is the difference between the electrical and gross efficiency of a motor?

15. What is the commercial efficiency of a 500 volt motor which takes a current of 120 amperes, the output being 71.6 horse-power? Ans. 89 %.

16. Explain how a differential compound motor gives a constant speed.

17. Why is it unnecessary to use a starting resistance for series motors on constant current circuits?

18. The torque exerted by a 35 horse-power motor is 335 foot-pounds. What number of revolutions per minute does it make? Ans. 549 r. p. m. (approx.).

19. In the preceding example what is the pull in pounds at the circumference of the pulley if the pulley is 20 inches in diameter? Ans. 402 pounds.

20. What is the great objection to reversing a motor while running?

21. Shunt motors have what great advantage?

22. Explain how by overwinding the field coils of a series motor, nearly constant speed may be obtained with varying load.

23. How may the necessity of shifting the brushes of a motor with change of load be largely prevented?

24. In what cases may series motors be used to advantage?

25. (*a*) What is a cumulative compound motor? (*b*) State its advantages.

26. Why are motors but little used on constant current circuits?

27. The differential motor has what serious disadvantage?

28. The counter E. M. F. of a shunt motor on constant potential mains has what value when the output is a maximum?

29. A motor is to be installed that is to be frequently stopped and started under a heavy load, and must have a nearly constant speed. What kind of a motor should be used?

30. It is desired to run a compound generator as a motor and in the same direction as when run as a generator. (*a*) What connections if any must be changed? (*b*) Will it be necessary to move the brushes?

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRICAL MEASUREMENTS.

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1. What is the distinction between fundamental and derived units?

2. What is meant by the dimensions of a physical quantity?

3. Describe a method of calibrating ammeters.

4. Explain why a voltmeter should have a high resistance and an ammeter a low resistance.

5. The ohm is equal to how many absolute units of resistance?

6. Upon what factors does the deflection of a galvanometer needle depend?

7. How may the resistance of a water rheostat be varied?

8. It is known that a coil of wire has an approximate resistance of 200 ohms, and it is desired to find its correct resistance tothe first decimal place by using the Wheatstone bridge. What should be the ratio of the bridge arms?

9. State the difference between the two general classes of galvanometers.

10. Give the advantages of the D'Arsonval galvanometer.

11. How many B. A. ohms are equal to 96 International ohms?

12. A galvanometer has a resistance of 5940 ohms and its shunt 60 ohms. What is the multiplying power of the shunt?

13. (*a*) What is the value of the kilowatt-hour? (*b*) How

many kilowatt-hours are expended by a current of 60 amperes in 8 hours and 45 minutes, the E. M. F. being 110 volts?

Ans. 24.75 kilowatts-hours.

14. When using the Wheatstone bridge why should the galvanometer key be closed after and opened before the battery key?

15. Explain why an astatic pair of needles is very sensitive to a slight current when the coil carrying the same is wound about one of the needles.

16. How may a galvanometer be used as a voltmeter?

17. Explain the principle of a differential galvanometer.

18. The E. M. F. of a Leclanche cell on open circuit as given by a voltmeter was 1.64 volts. After closing the cell through a certain external resistance, its E. M. F. fell to 1.10 volts, the current being .4 ampere. What was the resistance of the cell?

19. Describe the Weston voltmeter.

20. In Fig. 21 suppose the reversing key to be changed, and that a balance is obtained when $M = 1$, $N = 100$, and $P = 3{,}000 + 400 + 200 + 30 + 3 + 2$. What is the value of the resistance measured?

21. What are the disadvantages of electromagnetic ammeters?

22. In testing the insulation of a circuit by the voltmeter method, the voltmeter reading was 4.5 volts and the applied E. M. F. 220 volts. What was the insulation resistance in megohms, the voltmeter resistance being 17,000 ohms?

23. In making a high resistance measurement by the direct deflection method, the deflection obtained with .1 megohm resistance was 250 divisions. The unknown resistance gave a deflection of 20 divisions. In the former case the multiplying power of the shunt was 1000, and in the latter the shunt circuit was open. What was the unknown resistance?

24. What method should be used in testing the insulation of a 1,000 volt circuit?

25. (*a*) Describe an electrostatic voltmeter. (*b*) Give its advantages and disadvantages.

26. How is quantity determined by the Edison chemical meter?

27. (*a*) Standard resistance coils are made of what materials? (*b*) How are they wound, and why?

28. If the insulation resistance of 274 feet of wire is 13,500 megohms, what is the insulation resistance per mile?

29. In calibrating a voltmeter the resistance of the potentiometer used was 10,000 ohms. Three standard cells were used each having an E. M. F. of 1.435 volts. With a voltmeter reading of 86.4 volts, the cells balanced the fall of potential in 496 ohms. What was the error of the voltmeter at this reading?

30. In measuring the capacity of a condenser by the direct deflection method, it was found that a condenser of .2 microfarad capacity gave a deflection of 77 scale divisions, while the condenser of unknown capacity gave a deflection of 150 divisions. What was the capacity of the latter?

31. Describe the fall of potential method of locating faults in dynamos.

32. Describe the carbon rheostat.

33. What precautions should be taken when using standard cells?

34. In measuring the capacity of a condenser by the divided charge method, it was found that discharging the standard condenser through the galvanometer gave a deflection of 206 divisions. After again charging to the same potential as before, its charge was divided with the condenser whose capacity was desired, and on discharging gave a deflection of 110 divisions. If the capacity of the standard condenser was .1 microfarad, what was that of the other condenser?

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